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Authors
Arimond, Mary
Vitta, Bineti S
Martin-Prével, Yves
et al.

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ORIGINAL ARTICLE

Local foods can meet micronutrient needs for women in urban Burkina Faso, but only if rarely consumed micronutrient-dense foods are included in daily diets: A linear programming exercise

Mary Arimond[1] | Bineti S. Vitta[1] | Yves Martin-Prével[2] | Mourad Moursi[3] | Kathryn G. Dewey[1]

[1] Department of Nutrition, University of California Davis, Davis, California, USA
[2] Nutripass Research Unit, French National Research Institute for Sustainable Development, Montpellier, France
[3] HarvestPlus/International Food Policy Research Institute, Washington, District of Columbia, USA

Correspondence
Mary Arimond, Department of Nutrition, University of California Davis, 1 Shields Avenue, Davis, CA, 95616, USA.
Email: marimond@fhi360.org

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Abstract

Women of reproductive age are at nutritional risk due to their need for nutrient-dense diets. Risk is further elevated in resource-poor environments. In one such environment, we evaluated feasibility of meeting micronutrient needs of women of reproductive age using local foods alone or using local foods and supplements, while minimizing cost. Based on dietary recall data from Ouagadougou, we used linear programming to identify the lowest cost options for meeting 10 micronutrient intake recommendations, while also meeting energy needs and following an acceptable macronutrient intake pattern. We modeled scenarios with maximum intake per food item constrained at the 75th percentile of reported intake and also with more liberal maxima based on recommended portions per day, with and without the addition of supplements. Some scenarios allowed only commonly consumed foods (reported on at least 10% of recall days). We modeled separately for pregnant, lactating, and nonpregnant, nonlactating women. With maxima constrained to the 75th percentile, all micronutrient needs could be met with local foods but only when several nutrient-dense but rarely consumed items were included in daily diets. When only commonly consumed foods were allowed, micronutrient needs could not be met without supplements. When larger amounts of common animal-source foods were allowed, all needs could be met for nonpregnant, nonlactating women but not for pregnant or lactating women, without supplements. We conclude that locally available foods could meet micronutrient needs but that to achieve this, strategies would be needed to increase consistent availability in markets, consistent economic access, and demand.

KEYWORDS

Burkina Faso, diet, linear programming, micronutrients, supplements, women

1 | INTRODUCTION

Micronutrient intakes are often inadequate among women of reproductive age (WRA) living in resource-poor settings (Lee, Talegawkar, Merialdi, & Caulfield, 2013; Torheim, Ferguson, Penrose, & Arimond, 2010), with health consequences for both mothers and infants (Black et al., 2013). It is particularly challenging to meet intake requirements during pregnancy and lactation, due to elevated needs, and the World Health Organization recommends supplementation with iron and folic acid during pregnancy and calcium supplementation in populations with low dietary calcium intakes (WHO, 2016). Several developments in the last decade, including two landmark series in The Lancet (Horton, 2008; Maternal and Child Nutrition Study Group, 2013) and the organization of the Scaling Up Nutrition Movement (http://scalingupnutrition.org/) have served to refocus attention on the needs of adolescent girls and WRA, including on their diet quality and gaps. In this context, there have been several linear programming studies documenting the potential of local foods to meet micronutrient intake recommendations for WRA (Biehl et al., 2016; Pearson, 2013; Termote, Raneri, Deptford, & Cogill, 2014).

Our objective is to contribute to this growing literature with an example from urban Burkina Faso, for which high-quality dietary data were available and could be used to populate a local foods list and to define feasible quantities for consumption.

Linear programming is a flexible mathematical modelling technique that has been used for diverse purposes in relation to diets in developing countries, including to identify “problem nutrients” lacking in diets (Ferguson et al., 2006; Vitta & Dewey, 2012), to develop complementary feeding recommendations (Hlaing et al., 2016; Santika, Fahmida, & Ferguson, 2009) and food-based dietary guidelines (Levesque, Delisle, & Agueh, 2015; Ngala, Akter, Mwangi, & Brouwer, 2015), to formulate complementary foods (De Carvalho, Granfeldt, Dejmek, & Håkansson, 2015; Suri, Tano-Debrah, & Ghosh, 2014) and therapeutic foods (Bechman, Phillips, & Chen, 2015; Dibari, Diop el, Collins, & Seal, 2012), and to assess the role of fortified products in meeting needs (Baldi et al., 2013; Fahmida & Santika, 2016).

In the current application, the technique was used to identify the lowest cost diet using locally consumed foods and meeting micronutrient needs across a range of nutrients—if possible—with or without inclusion of supplements. More specifically, our objectives were to determine whether women's recommended micronutrient intakes could be achieved using

- only unfortified local foods, and if not, which micronutrients were most limiting in the diet; or
- unfortified local foods and a daily multiple micronutrient (MMN) tablet or a small-quantity lipid-based nutrient supplement (SQ-LNS), and if not, which micronutrients were most limiting in the diet.

Models and solutions were developed separately for pregnancy, lactation, and for nonpregnant, nonlactating (NPNL) women.

Key messages

- It is feasible to meet micronutrient needs of women in urban Burkina Faso using local foods, but only if women access and choose—on a daily basis—rarely consumed micronutrient-dense foods such as nuts, seeds, fresh and dried dark green leafy vegetables, specific nutrient-rich fruits, and liver.
- When only commonly consumed foods are included in daily diets in amounts typically consumed, needs for a range of micronutrients are not met.
- In the absence of rarely consumed foods, supplements may fill micronutrient gaps at lower cost than animal-source foods.
- Healthy dietary diversity that meets physical needs and cultural preferences remains the goal and should be pursued in policy and programmatic actions aimed at increasing consistent availability in markets, consistent economic access, and demand for micronutrient-dense foods.

2 | METHODS

2.1 | Dietary data source and setting

A previously analyzed food and ingredient-level data set was obtained from the Women's Dietary Diversity Project (http://www.fantaproject.org/research/womens-dietary-diversity-project). Dietary data were available from a study in Ouagadougou, Burkina Faso. Multiple days were included in the data set, and for the purposes of generating our food lists woman-days were considered as independent observations (e.g., to generate intakes per food per day). There were 705 woman-days from 182 women.

Data were from the last survey in a series of qualitative and quantitative explorations of food habits and dietary intakes conducted in the study area (Savy et al., 2008). The survey data were gathered with the aim of validating simple dietary diversity indicators as a measure of micronutrient adequacy among WRA.

The study was conducted in two districts of Ouagadougou, the capital city of Burkina Faso, in 2006. The city is divided into districts with amenities in the town center (called “structured districts”) and peripheral districts without amenities (called “nonstructured districts”). One “structured” district and one “nonstructured” district were purposively selected for the study because of the availability of demographic and socioeconomic data from an existing monitoring system. Comparison of study sample characteristics showed good agreement with Demographic and Health Survey data for Ouagadougou. We compared all variables that were available and comparable in both datasets (household size and composition; level of education of household head and of WRA; possession of assets including televisions, radios, refrigerators, bicycles, mopeds, and cars; quality of housing [roof, floor]; existence of amenities such as electricity, potable water, and latrines) and found no major differences in median values.

One weighed record and up to three nonconsecutive quantitative 24-hour recalls were gathered from each woman.

2.2 | Development of food lists and defining maximum quantities per day

Food or ingredient lists included all items consumed on any woman-day with the following exceptions: nondairy beverages; condiments, herbs, seasonings, and spices; sugars and sweeteners; sweets; and cooking agents. For some linear programming scenarios (see below), only items consumed on at least 10% of woman-days were allowed. There is no consistent definition in the literature of “rarely consumed foods.” Previous studies have used 10% and 25% (Darmon, Ferguson, & Briend, 2002); 5%, but with exceptions allowed for nutrient-dense uncommon foods (FANTA, 2014; Skau et al., 2014); and 10% (Ngala et al., 2015). We considered 10% as a reasonable criterion.

Because the number of food items allowed in our linear programming software was limited to 100, we further reduced food lists by selecting the most commonly consumed form of each specific food item, where nutrient values were very similar or identical. For example, boiled white rice using parboiled rice was selected for inclusion, and nonparboiled rice was dropped from the list, because parboiled rice was consumed much more frequently. Except for six items, the excluded items were either different forms of included foods, and/or were consumed on 2% or fewer woman-days. A small number of other food items were dropped because it was not possible to acquire price data.

To allow development of quantity constraints both at food item and at food group level, foods were organized into the following groups: cereals and grains; roots, tubers, and plantains; pulses and most legumes; nuts and seeds, including peanut; green leafy vegetables; any other vegetables; fruit; dairy; eggs; organ meats; any other meat or poultry; large fresh fish or shellfish; dried fish; and fats and oils.

We developed several sets of quantity constraints. The first reflected recalled consumption at the level of individual food items and the second at the level of the food group. To increase the likelihood of meeting needs, maxima were set at the 75th percentile of recalled consumption among consumers of each item. Table 1 shows food group maxima, and Table S1 shows maxima for individual food items. To further explore the potential of local foods when intake at the 75th percentile could not meet needs, we developed an additional set of food item and food group quantity constraints to explore higher quality diet scenarios using locally available foods but allowing higher quantities, based on servings and serving sizes recommended in national food-based dietary guidelines (FBDG). Because FBDG are not available for Burkina Faso, we used guidelines for Benin (Levesque et al., 2015). Table 2 shows food group level quantity constraints developed based on the guidelines and used in these models (hereafter, “food guide models”).

2.3 | Food prices

Food prices were obtained by a data collector who went to a local market and asked vendors for the prices of foods. Food prices were translated to U.S. dollars and used as the variable to minimize when obtaining solutions. The price of an MMN tablet was assumed to be 0.0123 USD based on the UNICEF Supply Catalogue (https://supply.unicef.org/, accessed Oct. 31, 2016), and the price of a 20 g sachet of SQ-LNS was assumed to be 0.061 USD based on the price of Enov'Mum, an SQ-LNS product produced by Nutriset (personal communication from Nutriset, November 29, 2016).

TABLE 1 Maximum allowed quantities per food group, based on the 75th percentile of intake

	75th percentile (g)
Grains	662
Roots, tubers, plantains	150
Dried beans, pulses	126
Nuts and seeds (includes peanut)	44
Leafy green vegetables (excludes culinary herbs)	110
Other vegetables	184
Fruit	360
Dairy products[a]	38
Eggs	60
Meat and poultry	68
Organ meat	16
Fish (large fresh or canned)	59
Fish (dried)	6
Fats and oils	40

[a]Fresh milk was consumed on only three woman-days, and dried milk powder was consumed on 42 woman-days; 38 g is the 75th percentile for consumption of milk powder.

2.4 | Nutrient content of foods and supplements

A food composition table (FCT) developed for the original study was used, as described in Becquey, Capon, and Martin-Prével (2009). The primary source FCT was the Table de Composition d'aliments du Mali (Barikmo, Ouattara, & Oshaug, 2004). The FCT was reviewed for outliers because linear programming solutions would be likely to select foods with high outlier values for nutrients. Nutrient data for three food items were replaced with more conservative values from a newer FCT (Food and Agriculture Organization, 2012). Two items with very high outlier values and not included in the newer FCT were dropped. For food items consumed raw, raw nutrient values were selected. For foods and ingredients consumed in cooked form, retention factors were applied to account for nutrient losses during cooking (United States Department of Agriculture, 2007).

The nutrient content of the multiple micronutrient tablet reflects the UNIMMAP tablet formulation (Margetts, Fall, Ronsmans, Allen, & Fisher, 2009), and the nutrient content of the SQ-LNS reflects the content of the International Lipid-Based Nutrient Supplements Project formulation for pregnancy and lactation (Arimond et al., 2015); details are in Table S2.

2.5 | Selection of micronutrients and recommended intakes

Micronutrients assessed in these analyses were the vitamins A, thiamin, riboflavin, B6, B12, folate and C, and the minerals calcium, iron, and zinc. These micronutrients were selected because they have been identified as the key “problem nutrients” for WRA, and there was adequate food composition information available for them in the source data set (Arimond et al., 2010).

The recommended nutrient intakes selected for our analysis were the lower of the Recommended Nutrient Intakes (RNI) or Recommended Safe Intakes from WHO/FAO (2004); or the Recommended Dietary Allowances (RDA) or Adequate Intakes from the Institute of Medicine (IOM) Dietary Reference Intakes (IOM, 2006, 2011). For iron and zinc, recommendations for absorbed nutrients were calculated by multiplying the RDA or RNI by the bioavailability assumptions used to formulate them. For zinc, the International Zinc Nutrition Consultative Group recommendations (IZiNCG et al., 2004) were also considered, and the lowest of the three recommendations was selected. We used the lowest recommendation for each nutrient to maximize the possibility of meeting needs using local unfortified foods. For calcium, in addition to using the U.S. RDA of 1000 mg, (equivalent to the WHO/FAO (2004) “Recommended calcium

TABLE 2 Maximum allowed quantities per food group, based on recommendations in the Benin food-based dietary guidelines[a]

	Servings				Servings to calculate maxima	Food group maxima
	NPNL[b]	Lactating	Pregnant			
Cereals, roots, and tubers[c]	4 to 6	5 to 6	4 to 6		5	675
Cereals				~60 g grains	Allow 5	300
Roots and tubers				~185 g tubers	Allow 3	555
Meat, fish, beans, and other sources of protein[d]	2 to 3	2 to 3	2 to 3	50 g legumes, 50 g dried fish, 75 g meat, 80 g eggs, and 100 g fresh fish	2.5	250
Vegetables[e]	4 to 6	4 to 6	4 to 6	Range from 50 g for leafy vegetables to 100 g for tomato and onion	5	500
Fruits[f]	2 to 3	2 to 3	2 to 3	Range from 75 g for banana to 150 g for papaya and pineapple	2.5	375
Milk products	1 to 2	1 to 2	1 to 2	20 g milk powder	1.5	30
Fats and oils[g]	2 to 3	2 to 3	2 to 3	20 g per spoon	2	40

[a]The Benin food guide was accessed from http://www.fao.org/nutrition/education/food-dietary-guidelines/home/en/ on June 1, 2016. The Benin food guide was used for Burkina Faso, because Burkina Faso does not have national dietary guidelines. The Benin guideline development process is documented in Levesque et al., 2015.

[b]NPNL = nonpregnant, nonlactating.

[c]Cereals, roots, and tubers are grouped in the food guide. In solutions, allowing five servings as the serving size for roots and tubers could allow implausible quantities for grains, if only grains are selected. To address this, a maximum for each type of grain was set at 5 × 60 g, with the same maximum for sum of all grains. A maximum was set at 3 × 185 for each type of root or tuber and for the sum of all roots and tubers. The maximum for cereals, roots, and tubers was set as (3 × 185) + (2 × 60) = 675; that is, the total grams implied by three servings of roots or tubers and two servings of grains.

[d]Groundnuts are included as an example in this group, but other nuts and seeds are not pictured in the food guide; serving sizes for other nuts and seeds are not specified. There are no serving size examples for organ meats. For purposes of scenarios, all are included; that is, total of meat, fish, beans, nuts, and eggs could not exceed 250 g. For constraints on individual items not included in the guide (seeds and organ meats), the 75th percentile of intake in the data set was used. For the food group maximum, the largest serving size (100 g) was multiplied by the midpoint of the recommended number of servings (2.5).

[e]There are no serving size examples given for dried leaves, and the 75th percentile of intake was used as a constraint for individual food items. For the food group maximum, the largest serving size (100 g) was multiplied by the midpoint of the recommended number of servings (5).

[f]There are no serving size examples given for dried or low moisture fruits (defined as <50% water content and including coconut, dates, tamarind, locust bean fruit, and baobab), so the 75th percentile was used as a constraint for individual items. For the food group maximum, the largest serving size (150 g) was multiplied by the midpoint of the recommended number of servings (2.5).

[g]Fats and oils are not pictured in the main graphic of the food guide, but a recommendation is provided on the pamphlet in the form of a moderation message, stating "Consume a small amount of vegetable oil, 2-3 spoons per day" for adults. The spoon size is defined as 20 g.

allowance" for NPNL women) we also ran models with the lower calcium level recommended by WHO/FAO for environments with lower animal protein intakes; these recommendations are set at 750 mg for adult women, including during lactation, and at 800 mg during the last trimester of pregnancy; we averaged across pregnancy and used a value of 767 mg for pregnancy. Tolerable upper intake levels (UL) from the U.S. IOM were not included as constraints in the models, but in instances where the UL was exceeded, this is reported in the results. The nutrient intake recommendations and UL are listed in Table S2. Throughout the paper, we use "recommended intake" to refer to the RNI or RDA (i.e., the average daily intake level sufficient to meet the needs of nearly all healthy individuals) and not to the estimated average requirement (EAR).

2.6 | Selection of macronutrient constraints

The U.S. IOM Acceptable Macronutrient Distribution Ranges (AMDR) were used as constraints in all models (IOM, 2005). The IOM AMDR were selected because the U.S. ranges for protein (10–35% of energy) and fat (20–35%) are broader than those of the World Health Organization (2003). As with selection of micronutrient intake recommendations, we aimed for constraints that would be more likely to result in solutions using local unfortified foods.

2.7 | Definition of energy content of solutions

In addition to considering micronutrient recommendations, models for feasible solutions need to incorporate consideration of energy intakes. For our analyses, we used two scenarios for energy intakes, for each physiological group. First, we ran scenarios using the calculated estimated energy requirements (EERs) based on the women's weights, heights, and a moderate physical activity level (IOM, 2005); EER were 2,329; 2,593; and 2,656 kcal for NPNL women, pregnant women, and lactating women, respectively. Next, as a sensitivity analysis, we constrained energy intakes to the median estimated energy intake in the data set (2,077 and 2,469 kcal for NPNL and lactating women, respectively). Energy intake data were not available for pregnant women because the subsample of pregnant women in the source data set was small. For pregnancy, we set the energy intake constraint at the median intake for NPNL women. Although energy requirements increase in pregnancy, in many settings, energy intakes of pregnant women may not increase substantially, especially in the first months of pregnancy.

2.8 | Linear programming methods and summary of constraints

We generated solutions for a range of scenarios (below) with the Microsoft Excel 2010 Solver software using the simplex algorithm. All our models included parameters and constraints as follows:

- food lists as defined above;
- solutions to include no more than the maximum quantities for food items and food groups, as defined above;
- solutions to meet recommended intakes for the 10 problem nutrients noted above (Table S2);
- solutions at a fixed level of energy intake, as defined above;
- solutions that fall within the U.S. IOM AMDR;
- solutions to include at least 30% of calories from starchy staple foods (any combination of grains, roots and tubers, and plantains); this value is substantially lower than the value of 56% observed in the study site.

Under these constraints, the lowest cost solution was generated for each scenario.

2.9 | Linear programming scenarios

In the following scenarios, foods are defined as "rare" if consumed on fewer than 10% of woman-days by women who participated in the dietary survey. We allowed fresh amaranth leaves in all scenarios, though they were consumed on only 9% of woman-days, because they were the most commonly consumed dark green leafy vegetable. Scenarios were

1. *No additional constraints on foods;*
2. *Rare foods excluded;*
3. *No additional constraints on foods, consumption of MMN tablet forced in;*
4. *Rare foods excluded, consumption of MMN tablet forced in;*
5. *No additional constraints on foods, consumption of 20 g SQ-LNS forced in;*
6. *Rare foods excluded, consumption of 20 g SQ-LNS forced in.*

These six scenarios were run using two energy constraints (EER and recalled) and with two levels of calcium intake recommendations, for 24 scenarios; this was done separately for each of the three physiological groups, resulting in 72 scenarios. Further, the 72 scenarios were run both with quantity maxima set at the 75th percentile of recalled food and food group intake, and following food guide quantities. However, results are reported for the food guide scenarios only when solutions could not be reached using the 75th percentile of reported intake as the maximum. When solutions were not possible even when quantities were allowed to increase to meet food guide recommended servings, models were modified by sequentially adding foods dense in limiting nutrients, until a solution was achieved.

In all scenarios, nutrients are considered as "constraining" either when recommended intakes are not met, are exactly met, or are met at less than 110%. We used this range in defining "constraining" nutrients because results from linear programming can be sensitive to small changes in parameters (for example, FCT values or prices). The "most limiting" nutrient in a solution might be second or third most limiting given a small shift in a single parameter. Thus, fixing on a single nutrient as limiting may not be warranted when results (percent of recommendation met) are similar for several nutrients.

3 | RESULTS

In scenarios in which maximum intake was constrained to the 75th percentile of recalled quantities and all local foods were allowed (including rarely consumed foods), solutions meeting all constraints were feasible for all physiological groups with local foods alone, with or without inclusion of MMN or SQ-LNS. In scenarios in which only commonly consumed local foods were allowed, solutions could not be achieved without supplements, for any physiological group. When common local foods were supplemented by MMN, solutions could be achieved only in the scenarios in which the lower calcium recommendation was used. When common local foods were supplemented by SQ-LNS, solutions were feasible in all scenarios and for all physiological groups. Table 3 summarizes results for scenarios with energy intakes set to the EER and with the lower calcium recommendation. Table 3 also indicates which micronutrients appeared to be most constraining (recommendations met at less than 110%).

When more liberal amounts of high-quality local foods were allowed, under the food guide scenarios, common local foods could meet all needs for NPNL women but still could not meet all needs during pregnancy or lactation. We sequentially relaxed quantity constraints further and/or added rare foods until solutions could be achieved. All "common foods" solutions for pregnancy and lactation required implausibly large quantities of dark leafy greens (150–250 g daily), in addition to ample (320–540 g) other fruits and vegetables as well as milk powder (a rarely consumed food) and either larger amounts of dried fish, or liver (another rarely consumed item; results not shown). These solutions were also more costly than those in Table 3, ranging from \$1.53–\$1.74/day.

Sensitivity analyses in which the EER were replaced with observed median energy intakes for each physiological group produced similar results (not shown), with two exceptions. In one scenario with the first set of quantity constraints (75th percentile), decreasing the energy intake changed the result in the MMN scenario for pregnant women, and no solution was possible. Conversely, in the scenario using food guide maxima, for lactating women, decreasing the energy constraint (at either level of calcium recommendation) allowed a solution in the common foods only scenarios, indicating that energy itself may be a constraint in some scenarios for lactating women.

Results in Table 3 also illustrate patterns related to constraining micronutrients. In the scenarios with no supplements, a number of micronutrients—riboflavin, vitamin B6, vitamin B12, folate, calcium, and iron—were below, at, or just over 100% in all solutions, indicating that these were the most difficult intake recommendations to achieve

TABLE 3 Results for linear programming scenarios with energy intake at EER, and meeting the lower WHO/FAO calcium recommendation[a]

	Solution	Cost[b] (U.S. $)	Micronutrients at 100–110% of target	Micronutrients <100% of target (%, if >90%)	UL exceeded
NPNL women, kcal = 2329					
All local foods allowed	Yes	0.51	Riboflavin, B6, B12, folate, calcium, iron	-	-
All local foods and MMN	Yes	0.48	B12, calcium	-	Iron
All local foods and SQ-LNS	Yes	0.50	Calcium	-	Zinc
Common local foods only*	**No**	1.45	Riboflavin, folate, calcium	B12	-
Common local foods and MMN	Yes	1.16	Calcium	-	Iron
Common local foods and SQ-LNS	Yes	0.54	Calcium	-	Zinc
*same scenario, with food guide maxima	Yes	0.85	Thiamin, B6, B12, folate, iron	-	-
Pregnancy, kcal = 2593					
All local foods allowed	Yes	0.65	Riboflavin, B6, B12, folate, iron	-	-
All local foods and MMN	Yes	0.53	B12, calcium	-	Iron
All local foods and SQ-LNS	Yes	0.55	Calcium	-	Zinc
Common local foods only*	**No**	1.48	Iron	Riboflavin, B6, B12, folate, calcium (98%)	-
Common local foods and MMN	Yes	1.45	Calcium	-	Iron
Common local foods and SQ-LNS	Yes	0.61	Calcium	-	Zinc
*same scenario, with food guide maxima	**No**	1.34	Riboflavin, B6, folate	B12	
Lactation, kcal = 2656					
All local foods allowed	Yes	0.67	Riboflavin, B6, folate	-	-
All local foods and MMN	Yes	0.55	B12, calcium	-	Iron
All local foods and SQ-LNS	Yes	0.56	Vitamin A, calcium	-	Zinc
Common local foods only*	**No**	1.49	Calcium	Riboflavin, B6, B12, folate (99%)	-
Common local foods and MMN	Yes	1.16	B12, calcium	-	Iron
Common local foods and SQ-LNS	Yes	0.62	Calcium	-	Zinc
*same scenario, with food guide maxima	**No**	1.49	Riboflavin, folate	B12	

[a]EER = estimated energy requirement based on the womens' weights, heights, and a moderate physical activity level (IOM, 2005); MMN = multiple micronutrient tablet; NPNL = nonpregnant, nonlactating; SQ-LNS = 20 g of small-quantity lipid-based nutrient supplement. The lower calcium recommendation is the WHO/FAO (2004) theoretical calcium allowance based on an animal protein intake of 20–40 g. EER were 2,329; 2,593; and 2,656 kcal for NPNL women, pregnant women, and lactating women, respectively.

[b]Cost per day in U.S. dollars, calculated based on the exchange rate of March 3, 2017.

using local foods only. In scenarios that included supplements, fewer nutrient were constraining. In scenarios that included MMN, calcium was consistently at or just over 100%, and as noted was below 100% in scenarios in which the higher calcium recommendation was applied. Vitamin B12 intake recommendations were also difficult to achieve in some scenarios. In the scenarios including SQ-LNS, calcium recommendations could be met, at either the high or low level, but calcium remained the most constraining nutrient.

The UL for iron was exceeded in nearly all scenarios that included MMN, with iron levels in the solutions ranging up to 65.3 mg, compared to the UL of 45 mg. For scenarios with SQ-LNS, the UL for zinc was exceeded in most scenarios, and the UL for iron was exceeded in several. Zinc levels in the SQ-LNS solutions ranged up to 43.8 mg, compared to the UL of 40 mg, and iron ranged up to 49.6 mg.

Table 4 shows the food items and quantities of food selected in the scenarios for NPNL women with the lower calcium recommendation. We selected scenarios with the lower calcium recommendation for presentation, because all solutions included very low levels of animal protein intake, ranging from 0 to 14 g. Solutions for scenarios with the higher recommended intake for calcium were generally similar in regard to selected food items. Tables S3 and S4 show results for pregnant and lactating women; scenarios for all three physiological groups were similar with respect to food items selected and balance between food groups.

Dairy products, eggs, and large fresh fish did not appear in any solutions, probably due to cost. All solutions included grains, dried beans, nuts and/or seeds, dark green leafy vegetables, and fat or oil. All local foods solutions without supplements included liver (when rare foods were allowed) or both meat and fish (common foods scenarios) but in small quantities, and in the common foods scenarios, quantities were insufficient to meet vitamin B12 recommendations. Fruits and vegetables other than dark green leafy vegetables were selected only when rarely consumed foods could not be selected; they were selected

TABLE 4 Foods selected in linear programming scenarios for NPNL women when maximum quantity constraint is the 75th percentile of estimated intake[a]

	Maximum allowed	All local foods			Common local foods[b]		
		No supplement	MMN	SQ-LNS	No supplement	MMN	SQ-LNS
Grains							
Rice, white, polished, g	246	0	0	0	143	144	127
Maize flour, white, g	267	168	267	237	0	0	267
Pearl millet, flour, g	99	0	0	0	99	99	0
Wheat flour, white, g	97	0	0	0	97	97	0
Sorghum flour, g	*195*	*195*	*195*	*195*	*0*	*0*	*0*
Sum of grains in solutions, g		363	462	433	338	339	394
As percent of maximum allowed for group (662 g)		55%	70%	65%	51%	51%	59%
Roots, tubers, plantains							
Sweet potato, white, raw, g	*150*	*32*	*0*	*0*	*0*	*0*	*0*
Sum of roots, tubers, plantains in solutions, g		32	0	0	0	0	0
As percent of maximum allowed for group (150 g)		21%	0%	0%	0%	0%	0%
Dried beans, pulses							
Black eyed peas, mature, dried, g	126	83	14	19	104	126	80
Sum of beans, pulses in solutions, g		83	14	19	104	126	80
As percent of maximum allowed for group (126 g)		66%	11%	15%	83%	100%	64%
Nuts and seeds (includes peanut)							
Soumbala, fermented seed of African locust bean, g	4	3	0	0	4	4	0
Peanut paste/pounded, g	44	0	0	0	39	39	0
Peanuts, fresh, roasted, g	31	13	0	21	0	0	31
Hibiscus/Sorrel seed, fermented, g	*18*	*0*	*11*	*18*	*0*	*0*	*0*
Baobab fruit seed, dried, g	*5*	*0*	*5*	*5*	*0*	*0*	*0*
Sesame seed, whole, dried, g	*28*	*28*	*28*	*0*	*0*	*0*	*0*
Sum of nuts, seeds, in solutions, g		44	44	44	44	44	31
As percent of maximum allowed for group (44 g)		100%	100%	100%	100%	100%	70%
Leafy green vegetables (excl. Culinary herbs)							
Amaranth leaves, fresh, raw, g	110	12	20	0	110	110	105
Baobab leaves, dried, g	*28*	*28*	*28*	*27*	*0*	*0*	*0*
Sum of leafy green vegetables in solutions, g		40	49	27	110	110	105
As percent of maximum allowed for group (110 g)		36%	44%	25%	100%	100%	95%
Other vegetables							
Onion, raw, g	36	0	0	0	36	36	0
Cabbage, raw, g	68	0	0	0	68	68	0
Bell pepper, green, raw, g	5	0	0	0	5	5	0
Eggplant, raw, g	30	0	0	0	28	28	0
Zucchini, raw, g	34	0	0	0	34	34	0
Okra, raw, g	13	0	0	0	13	13	0
Sum of other vegetables in solutions, g		0	0	0	184	184	0
As percent of maximum allowed for group (184 g)		0%	0%	0%	100%	100%	0%
Fruit							
Mango, ripe, raw, peeled, g	360	0	0	0	360	278	0
Coconut, mature kernel, fresh, g	*46*	*6*	*0*	*0*	*0*	*0*	*0*
African locust bean, fruit, raw, g	*50*	*50*	*0*	*0*	*0*	*0*	*0*
Sum of fruits in solutions, g		56	0	0	360	278	0
As percent of maximum allowed for group (360 g)		15%	0%	0%	100%	77%	0%
Meat and poultry							
Mutton, little fat, raw, g	33	0	0	0	33	0	0
Beef, little fat, raw, g	25	0	0	0	25	0	0
Sum of meat and poultry in solutions, g		0	0	0	58	0	0

(Continues)

TABLE 4 (Continued)

	Maximum allowed	All local foods			Common local foods[b]		
		No supplement	MMN	SQ-LNS	No supplement	MMN	SQ-LNS
As percent of maximum allowed for group (68 g)		0%	0%	0%	86%	0%	0%
Organ meat							
Liver, sheep, raw, g	*16*	*4*	*0*	*0*	*0*	*0*	*0*
Sum of organ meat in solutions, g		4	0	0	0	0	0
As percent of maximum allowed for group (16 g)		22%	0%	0%	0%	0%	0%
Fish, dried							
Catfish, whole, dried, g	6	0	0	0	6	6	0
Sum of dried fish in solutions, g		0	0	0	6	6	0
As percent of maximum allowed for group (6 g)		0%	0%	0%	100%	100%	0%
Fats and oil							
Cottonseed oil, g	36	0	13	13	12	25	36
Peanut oil, g	19	0	0	0	0	0	4
Shea butter, g	*27*	*27*	*27*	*27*	*0*	*0*	*0*
Sum of fats and oil in solutions, g		27	40	40	12	25	40
As percent of maximum allowed for group (40 g)		68%	100%	100%	30%	63%	100%

Note. MMN = multiple micronutrient tablet; NPNL = nonpregnant, nonlactating; SQ-LNS = 20 g of small-quantity lipid-based nutrient supplement.

[a]Solutions for scenarios with energy at the estimated energy requirement (2329 kcal) based on the womens' weights, heights, and a moderate physical activity level (IOM, 2005) and calcium at the lower WHO/FAO (2004) level (theoretical calcium allowance based on an animal protein intake of 20–40 g). The 75[th] percentile was calculated considering consumers only. Some percentages appear slightly off due to rounding. Food groups (dairy, eggs, and fresh fish) and food items that were not selected are not listed.

[b]Common foods are those consumed on at least 10% of woman-days. Food items in italics were consumed on fewer than 10% of woman-days and are excluded from "common foods" scenarios.

in common foods scenarios with no supplements, and with MMN, but were not selected in the common foods scenarios with SQ-LNS.

Several rarely consumed foods or groups were consistently selected, when allowed. These included sorghum, several seeds, dried baobab leaves, and shea butter. In addition, liver and several rarely consumed fruits were selected in the unsupplemented scenarios. These foods are either cheaper sources of energy (shea butter), more nutrient-dense and lower cost than other items within the same food group (sorghum), or particularly nutrient-dense (seeds, dried leaves, liver, and several fruits); some of these last foods are also energy-dense.

Table 5 translates the solutions in Table 4 into servings and compares them to the recommended number of servings in the Benin food guide. There are some deviations from recommendations, which may reflect our use of quantity constraints based on actual diet patterns. Servings of starchy staples exceeded recommendations in a number of scenarios and tended to be higher in scenarios with supplements. Servings of protein-rich foods also exceeded recommendations except in the SQ-LNS scenarios, but protein-rich foods were primarily from plant sources (legumes, nuts, and seeds); these foods were likely selected as low-cost sources of several minerals, as well as protein. The number of servings of vegetables was low in four of six scenarios for each physiological group and was adequate only in the unsupplemented common foods scenarios and the common foods scenarios with MMN. The number of servings of fruit was also low in several scenarios and was "0" in a number of the scenarios with supplements. As noted, dairy foods were not selected in any scenario. The number of servings of fats or oils was low in several scenarios, but this was compensated for by intake of nuts and seeds, and all the diets met the AMDR including the minimum criterion for percent of energy from fats.

4 | DISCUSSION

Linear programming scenarios constrained to represent realistic maximum intakes (75th percentile of reported quantities) indicate that it is possible to meet all micronutrient needs for WRA in urban Burkina Faso, so long as several nutrient-dense, but rarely consumed items are included in daily diets. These same scenarios based on local foods provided sufficient energy (defined as the average EER) and were within AMDR for all physiological groups. However, when diets were constrained to include only commonly consumed foods, defined as those present in dietary recalls for at least 10% of observation days, micronutrient needs could not be met without supplements. With inclusion of MMN, all needs could be met if a lower calcium recommendation was used, but diets could not achieve the higher target of 1,000 mg calcium while simultaneously meeting all other constraints. With inclusion of SQ-LNS, all needs could be met.

Our modelling results showing that commonly consumed foods could not meet micronutrient needs are consistent with the low probability of micronutrient adequacy previously reported for this group of WRA (Becquey & Martin-Prevel, 2010); probability of adequacy was below 50% for thiamin, riboflavin, niacin, folate, vitamin B12, calcium, and iron and was below 75% for vitamins B6, A and C, and zinc.

These results reflect a context in which dairy foods were very infrequently consumed, and in small quantities. To meet even the lower WHO/FAO calcium level, the Excel Solver algorithm selected

TABLE 5 Servings per food group compared to servings in the Benin food guide[a] in linear programming scenarios when maximum quantity constraint is the 75th percentile of estimated intake[b]

	Food guide	Scenarios allowing all local foods			Scenarios allowing common foods[c]		
		No supplement	MMN	SQ-LNS	No supplement	MMN	SQ-LNS
NPNL women							
Cereals, roots and tubers	4 to 6	6.2	7.7	7.2	5.6	5.6	6.6
Meat, fish, beans, and other sources of protein	2 to 3	4.4	3.4	2.5	4.4	4.1	2.2
Legumes, nuts and seeds		4.1	3.4	2.5	3.2	3.6	2.2
Meat, organ meat, dried fish		0.2	0.0	0.0	1.2	0.4	0.0
Vegetables	4 to 6	2.1	2.3	1.8	5.0	5.0	2.1
Fruits	2 to 3	3.7	0.0	0.0	3.6	2.8	0.0
Milk products	1 to 2	0.0	0.0	0.0	0.0	0.0	0.0
Fats and oil	2 to 3	1.4	2.0	2.0	0.6	1.3	2.0
Pregnancy							
Cereals, roots and tubers	4 to 6	6.4	7.8	7.7	6.3	6.3	7.6
Meat, fish, beans, and other sources of protein	2 to 3	5.9	3.8	2.6	4.8	4.5	2.5
Legumes, nuts and seeds		5.7	3.8	2.6	3.6	3.6	2.5
Meat, organ meat, dried fish		0.3	0.0	0.0	1.2	0.9	0.0
Vegetables	4 to 6	3.5	2.2	1.9	4.4	5.0	2.1
Fruits	2 to 3	4.9	3.1	1.7	3.6	3.6	0.0
Milk products	1 to 2	0.0	0.0	0.0	0.0	0.0	0.0
Fats and oil	2 to 3	1.4	2.0	2.0	0.9	1.1	2.0
Lactation							
Cereals, roots and tubers	5 to 6	7.1	8.1	7.7	6.5	7.0	7.5
Meat, fish, beans, and other sources of protein	2 to 3	4.7	3.9	2.4	4.8	4.0	3.0
Legumes, nuts and seeds		4.0	3.9	2.4	3.6	3.6	3.0
Meat, organ meat, dried fish		0.7	0.0	0.0	1.2	0.5	0.0
Vegetables	4 to 6	3.5	2.1	1.9	4.4	5.0	1.9
Fruits	2 to 3	5.4	3.1	2.1	3.6	2.2	0.0
Milk products	1 to 2	0.0	0.0	0.0	0.0	0.0	0.0
Fats and oil	2 to 3	1.4	2.0	2.0	0.9	1.8	2.0

Note. MMN = multiple micronutrient tablet; NPNL = nonpregnant, nonlactating; SQ-LNS = 20 g of small-quantity lipid-based nutrient supplement.

[a]Dietary guidelines were accessed from http://www.fao.org/nutrition/education/food-dietary-guidelines/home/en/ on June 1, 2016. The Benin Food Guide was used for Burkina Faso, since Burkina Faso does not have national dietary guidelines. The Benin guideline development process is documented in Levesque et al., 2015.

[b]Solutions for scenarios with energy at the estimated energy requirement (EER) based on the women's weights, heights, and a moderate physical activity level (IOM, 2005) and calcium at the lower WHO/FAO (2004) level (theoretical calcium allowance based on an animal protein intake of 20–40 g). EER were 2,329; 2,593; and 2,656 kcal for NPNL women, pregnant women, and lactating women, respectively.

[c]Common foods are those consumed on at least 10% of woman-days.

relatively affordable and calcium-rich grains, seeds, and dark green leafy vegetables, and calcium remained the most consistently limiting nutrient in scenarios that included supplements.

In scenarios allowing up to the 75th percentile for food item intake, and without supplements, several nutrients were constraining, including riboflavin, vitamin B6, vitamin B12, folate, calcium, and iron. Vitamin B12 needs were particularly difficult to meet given the low levels of intake of animal-source foods, even at the 75th percentile of observed consumption.

To explore whether “common foods” scenarios that allowed more liberal amounts of animal-source foods could meet needs, a second set of food quantity limits were developed based on the Benin food guide. When larger amounts of animal-source foods were allowed, all needs could be met for NPNL women, but no solution meeting all needs was feasible for pregnant or lactating women. When we modified constraints further until solutions were achieved, the resulting diets were not plausible for daily consumption.

Solutions that included MMN usually exceeded the UL for iron, and those including SQ-LNS usually exceeded the UL for zinc and sometimes for iron. For iron, the UL of 45 is based on avoiding gastrointestinal side effects, but these are mainly experienced when iron is taken in supplements as a bolus dose. Gastrointestinal distress has not been reported from diets high in naturally occurring or fortificant iron (IOM, 2001). The maximum amounts in our scenarios were 65.3 mg iron in MMN scenarios and 49.6 mg in SQ-LNS scenarios; it is worth noting that the WHO has recommended up to 60 mg iron for routine use during pregnancy for many decades. For zinc, the UL of 40 mg was exceeded by a small amount in some scenarios that included SQ-LNS (up to 43.8 mg), but again, the main adverse effect of high doses is gastrointestinal effect. These or other supplements can be tailored to the target population to avoid potential adverse effects. For example, iron and zinc contents could be reduced if simulations of the population-wide effects of scaling up such interventions suggest that intakes of a sizeable proportion of the target population would exceed the UL.

We note that all solutions based on local foods that met needs required inclusion of a range of specific, nutrient-dense foods, and this would require both consistent access and behavior change; that is, consistent selection and consumption of these rarely consumed foods. We do not have information on barriers, but these could include availability, access, facilities for storage of fresh foods, and preferences, including for taste and convenience, and preferences of other household members. Cost is likely to be a constraint in "food guide" solutions that included increased consumption of animal-source foods to meet needs.

Several previous studies have employed linear programming to assess the feasibility of meeting micronutrient needs for WRA using locally available, unfortified foods. Pearson (2013) identified a range of problem nutrients in the diets of lactating women in Kwazulu-Natal, South Africa, and modeled a number of scenarios exploring the potential of local plant foods to fill the gaps. Excluding vitamins B12 and D, which were identified as problem nutrients but were not targeted in this study of plant foods, gaps in intake of problem nutrients could be filled for half of women (i.e., intakes could reach approximately the EAR) in modified local diets in which 54 g of maize meal was replaced by 250 g of leafy vegetables and 350 g of fruit.

Biehl et al. (2016) modeled both household and individual diets, including for WRA, in three agroecological zones in Nepal. Calcium was most consistently limiting for women, vitamin B12 was extremely low in two of three zones, and riboflavin was also a problem nutrient. It was not possible to meet needs when quantities were constrained to reflect consumption patterns. Optimized diets meeting needs were possible with relaxed quantity constraints and the addition of dark green leafy vegetables and small fish. The authors concluded that without adding small fish, it was not possible to meet calcium and B12 needs without compromising ability to meet targets for other nutrients or substantially increasing cost.

Working in Baringo District, Kenya, Termote et al. (2014) used linear programming in an exploratory study to screen wild foods for their potential to reduce cost and meet nutrient needs of vulnerable individuals, including WRA. They identified four wild fruits and one wild leafy green that filled gaps in adequacy of iron and zinc for WRA while reducing the cost of adequate diets.

Linear programming has also been used in the development of FBDG, including for WRA, in Benin (Levesque et al., 2013) and Kenya (Ngala et al., 2015). In the Benin example, solutions could not be achieved for women in some or all physiological groups without relaxing nutrient recommendations for folate, calcium, iron, and zinc to 70% of the RNI. Further, to meet needs, dairy products were "forced" into the models, and meat portion sizes were increased relative to local consumption patterns. Ngala et al. (2015) aimed to develop FBDG specifically for WRA in Eastern Kenya. Diets meeting 100% of all RNI were not feasible, so FBDG were developed that met 70% of the RNI for energy, protein, thiamin, riboflavin, pantothenic acid, vitamins A, B6, and C, and calcium and zinc. It was not feasible to meet even 70% of the RNI for vitamin B12, folate, or iron based on available foods, and the authors concluded that alternative strategies would be required to meet these needs.

Taken together, these studies and our own are broadly consistent and underline both the potential and the challenge of using local foods to fill nutrient gaps for WRA. These studies and ours are also consistent with previous reviews that have identified multiple problem micronutrients in the diets of WRA, including thiamin, riboflavin, niacin, vitamins B6 and B12, folate, calcium, iron, and zinc (Lee et al., 2013; Torheim et al., 2010).

Our study has a number of limitations. Because some items were rarely consumed, some maximum quantity constraints were based on limited data; however, we reviewed each constraint and in one case (sesame seeds) substituted a value for two servings for one implausible maximum, and food-group-level constraints also helped prevent implausible intakes in solutions.

Second, many of the items in our solutions would typically be consumed in mixed dishes, and the solutions do not represent existing recipes for composite foods; thus, the solutions we report are not intended as recommendations nor do they necessarily represent feasible and culturally acceptable combinations of specific foods for daily consumption. In addition to issues of feasibility and acceptability, some items in our solutions may be available only seasonally; for example, mango was consumed on 24% of woman-days and was an allowed food in all scenarios. Nevertheless, taken at the level of the food group, our results suggest patterns that could meet needs.

Third, in common with other studies that include local and wild food items, food composition values were difficult to verify and in some cases represent small numbers of samples of foods and from different geographic areas. As noted by others (e.g., Termote et al., 2014), lack of reliable food composition data for neglected and wild species restricts analyses; in our example, we deleted several food items from consideration because of apparent extremely high outlier values for specific nutrients, which we could not verify, thus potentially excluding promising foods.

Fourth, in line with our objectives, we modeled the potential contribution of MMN tablets and SQ-LNS, but we did not model the potential contribution of biofortified foods or fortified food products targeted at the general population. These foods and products are not targeted to meet the high needs of WRA during pregnancy and lactation but can play a role in filling gaps.

Finally, due to the limitations in our cost data, we cannot make strong conclusions about relative costs of solutions, including across seasons. In addition to nonrepresentative cost data for foods, our prices for supplements do not include delivery costs. Therefore, costs of solutions, as presented in Table 3, are quite imprecise. Further, because we have no household income or expenditure data for the study households, we cannot comment on affordability. However, large differences in cost may be meaningful and can be interpreted in combination with the food items selected, shown in Table 4 and Tables S3 and S4. When rarely consumed foods were allowed, costs of solutions were roughly similar. However, when only common foods were allowed, the costs for the nonsupplemented solutions and the MMN solutions were substantially higher than the SQ-LNS solutions for all three physiological groups. This can be explained by the selection of a range of vegetables, fruits, and flesh foods, which were all absent in the SQ-LNS solutions. Although highly desirable, inclusion of these food groups in diets appears to increase the cost of meeting micronutrient needs and would do so even if the cost of the SQ-LNS were assumed to be substantially higher.

5 | CONCLUSIONS

Diets of WRA lack a range of micronutrients, and existing programs providing iron and folic acid do not address the full range of important gaps. Locally available foods could meet micronutrient needs of WRA in urban Burkina Faso and similar settings if successful strategies can be found to increase the proportion of women regularly consuming nutrient-dense grains (e.g., sorghum), nuts, seeds, fresh and dried dark green leafy vegetables, specific nutrient-rich fruits, and liver. Required quantities are within current consumption patterns (in 2006) albeit at the higher end of reported consumption. To achieve the needed changes, strategies would likely be needed to increase both consistent availability in markets and consistent economic access and also to increase demand. Special attention should be given to ensure identification and promotion of low-cost nutrient-dense foods, identified in our models and in other studies, and likely to be present in many settings.

Diverse diets including fruits, vegetables, legumes, nuts, and whole grains are recommended by the World Health Organization[1] and provide not only micronutrients but also fiber, healthy fats, and a wide range of bioactive phytochemicals with known—and likely unknown—benefits for human health (Norden, 2014). In addition to healthy diversity in plant food intakes, WRA require animal-source foods or supplements to meet B12 recommendations and high needs for several other micronutrients, especially during pregnancy and lactation. Although use of supplements to fill gaps can also be considered and, in some contexts, will provide a lower cost alternative to animal-source foods, healthy dietary diversity that meets physical needs and cultural preferences remains the goal and should be pursued in policy and programmatic actions.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

KGD and BSV developed the study concept. YMP oversaw data collection. KGD, BSV, and MA developed the analysis plan; YMP and MM commented on the analysis plan. BSV and MA analyzed data. MA wrote the paper. All authors commented on drafts and approved the final version of the manuscript.

[1]http://www.who.int/mediacentre/factsheets/fs394/en/, accessed Oct 20, 2016.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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