Costing Healthy Diets and Measuring Deprivation: New Indicators and Modeling Approaches

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Abstract—One of the greatest global challenges today is ensuring widespread availability and equitable access to affordable, nutritious foods produced in an environmentally sustainable manner. A rich literature exists around the definition of a healthy diet and the drivers of dietary change. We contribute to this literature by proposing a new quantifiable diet deprivation measure estimated from standard household consumption and expenditure surveys. The Reference Diet Deprivation (ReDD) index measures the incidence, breadth, and depth of diet deprivation across multiple, essential food groups in a single indicator. Although useful as a standalone measure, we show how ReDD can be integrated into an economywide model to examine changes in household diet quality under different simulation scenarios. Using Nigeria as case study, hypothetical agricultural productivity growth scenarios reveal that dairy, pulses, fruit, and red meat value chains have the greatest potential to reduce overall diet deprivation in Nigeria per unit of GDP growth generated, while productivity growth in more widely consumed crops such as cereals and root crops do little to improve diet quality. These findings have implications for the prioritization of agricultural development initiatives aimed at improving the quality of diets. More generally, the integration of a diet quality indicator in an economywide model allows for a deeper understanding of the drivers of dietary change.

Keywords—Diet quality; diet deprivation; affordability of healthy diets; dietary change; dietary guidelines; consumer behavior; economywide modeling; Nigeria

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1 Introduction

Poor diet quality, as it relates to deficiencies, excesses, or imbalances in people's caloric and nutrient intakes, is universally recognized as one of the leading causes of malnutrition and non-communicable diseases (Afshin, et al. 2019, FAO, IFAD, UNICEF, WFP and WHO 2020). Alongside diet-related health concerns, the environmental sustainability of food supply systems, which are increasingly associated with rising emissions and pollution, biodiversity loss, and unsustainable water and land use, has come into question. This served as motivation for the EAT-*Lancet* Commission to develop a healthy reference diet that specifies ranges of food intakes for major food groups, which combined in a diet, would optimize human health. Further, if all people consumed that diet, the world would remain within the planetary boundaries for sustainable food production (Willett, et al. 2019).

Human diets are shaped by complex food systems and are highly context specific. As a consequence, although there are broadly accepted guidelines for what constitutes healthy eating—for example, diets should meet requirements for dietary energy and essential nutrients and avoid excess intake of less desirable foods, unhealthy food components, or non-essential nutrients (Tapsell, et al. 2016, Afshin, et al. 2019)—there is no single, globally accepted definition of a healthy diet (Vermeulen, et al. 2019). For this reason, reference diets such as the EAT-*Lancet* healthy reference diet (hereafter referred to as the ETA-*Lancet* diet), while consistent with those dietary guidelines, tend to be broadly defined and non-prescriptive (Willett, et al. 2019). This flexible approach to defining healthy diets makes it difficult to definitively rank or compare the quality of diets. However, having the ability to empirically measure diet quality is nevertheless useful and important from a monitoring and evaluation perspective.

Beyond an interest in measuring diet quality, policymakers may also wish to understand the drivers of dietary change. Consumer behavior is a key driver of diet choice, but this behavior is not independent of the broader food system (Ruel, Leroy, et al. 2020, GLOPAN 2016). Instead, behavior is linked to food environments, i.e., the places and contexts in which consumers access food, as shaped by personal circumstances, norms, markets, and policies. Food environments, in turn, are intrinsically linked to food supply chains, which encompass production, storage, processing, and marketing of food. These interlinked components of the food system—consumer behavior, food environments, and supply chains—are further influenced by demographic, socio-cultural, political, economic, technological, and environmental drivers (Turner, et al. 2018, Swinburn, et al. 2013). Not only does the complexity of the food system create many entry points or levers through which policies or investments can influence diets, but the interconnectedness of the various components within the system implies that policies that influence one component can have consequences for others.

With this context in mind, we have two objectives in this paper. The first is to introduce a new diet outcome measure called the Reference Diet Deprivation (ReDD) index. The ReDD methodology is inspired by the Multidimensional Poverty Index (MPI) (Alkire and Foster 2011). However, whereas the MPI is usually applied in the context of deprivation in non-monetary dimensions of wellbeing, such as education, health, or standards of living, the ReDD index considers food consumption deprivation within and across major food groups. Specifically, the ReDD index is computed using household consumption and expenditure survey data and involves a comparison of per capita food consumption across six major food groups against reference consumption thresholds as defined by a selected reference diet. The index itself is a compound measure of the three separate indicators measuring the incidence, breadth, and depth of diet deprivation. The ReDD index can be based on food expenditures or calorie availability as the measurement of consumption.

The second is to showcase how ReDD can be integrated into an economywide modeling framework to examine changes in household diet quality under different policy or investment scenarios or external shocks. The Rural Investment and Policy Analysis (RIAPA) model developed by the International Food Policy Research Institute (IFPRI) incorporates a recursive-dynamic computable general equilibrium (CGE) model that captures the interactions of all producers and consumers in an economy (Diao and Thurlow 2012). A unique feature of RIAPA is its detailed representation of the agri-food system, making it ideally suited to examine implications of policies, investments, or shocks on food supply, household food budgets, and relative food prices, which in turn drive dietary change via their impacts on the food environment. Using Nigeria as case study, we conduct hypothetical agricultural value chain productivity growth scenarios to identify those value chains that are most effective at reducing the incidence, breadth, and depth of diet deprivation as measured by the ReDD index. Changes in the ReDD index are computed in a survey-based microsimulation model linked sequentially to RIAPA.

The paper is structured as follows. Section 2 introduces key concepts, including reference diets, diet costing, and the mathematical derivation of ReDD. Section 3 introduces the RIAPA model and the diet module used to compute the ReDD index. Section 4 presents the simulation setup and results; and Section 5 draws conclusions.

2 Measuring diet deprivation

2.1 Overview

The ReDD index is a multidimensional indicator of household diet deprivation. The measure is multidimensional as it compares households' per capita consumption across six essential food groups—staples, vegetables, fruits, dairy foods, protein foods, and added fats—against reference consumption amounts obtained from a reference diet. A household is considered deprived in a food group if it fails to meet the reference consumption amounts. The ReDD index itself is a compound measure of three separately measured elements: the share of the population that is deprived in one or more food groups (incidence of deprivation); the average number of food groups in which consumers are deprived (breadth of deprivation); and the relative average gap between observed consumption and reference thresholds (depth of deprivation).

The ReDD index is computed using household consumption and expenditure survey data. These surveys measure food consumption in monetary terms and often also in quantity terms (e.g., grams). Food consumption ranges or targets specified in reference diets are typically defined in terms of food quantities. Two approaches to computing the ReDD index are proposed. The first is an expenditure-based approach (ReDD-X) where per capita expenditure by food group is compared against a reference cost of that food group. The second is a calorie-based approach (ReDD-C) where household per capita calorie availability by food group is compared against calorie amounts derived from reference food quantities. This approach can be adopted if household surveys include estimates of food quantities, and the food categories of the consumption recalls are specified in sufficient detail to convert food quantities into accurate calorie amounts. In the absence of suitable calorie conversion factors, the measure could also be based directly on food consumption quantities (ReDD-Q) rather than expenditures or calories. However, this study only presents estimates for ReDD-X and ReDD-C given familiarity with food expenditure or calorie availability in the context of diet analysis. It is also more intuitive to define a minimum requirement for the overall diet in terms of overall food expenditure or calories rather than in terms of quantities.

ReDD has three useful features. First, since it measures deprivation at the level of the household, it recognizes that even when national food supplies are adequate, there is inequality in the access and utilization of food (Barrett 2010). Second, as a multidimensional (or multi-food group) diet deprivation measure, ReDD indirectly measures diet quality in that it incorporates elements of both nutrient (in)adequacy and (a lack of) dietary diversity. Since dietary diversity indicators are positively associated with diet quality (Ruel, Harris and Cunningham 2013, Ruel 2003), ReDD is likely to be inversely associated with diet quality. Third, whereas dietary diversity scores are categorical indicators (i.e., count measures), the information content in the ReDD index is richer in that it incorporates information both on whether a food group is consumed and the extent of consumption shortfalls, where relevant. Moreover, as a continuous, quantifiable variable that is sensitive to marginal changes in household incomes and relative food prices, the ReDD index is suited for integration in an economic model, as we demonstrate later.

2.2 Reference diets

The first step for either of the ReDD approaches is choosing an appropriate reference diet. In principle, any diet that defines reference food intakes by food group can be used. A reference diet might be constructed from national food-based dietary guidelines. Alternatively, a global reference diets such as the EAT-*Lancet* healthy reference diet can be used (Willett, et al. 2019). The EAT-*Lancet* diet is used as our default reference diet, although the concepts and methods apply equally to other global reference diets, such as the flexitarian, pescatarian, or vegetarian diets proposed by Springmann et al. (2018).

Reference food intake quantities for the EAT-*Lancet* diet, specified in grams per capita per day, are reported in Table 1. The EAT-*Lancet* diet consists of eight major food groups (Willett, et al. 2019). The first two are whole grains and root crops, which we combine into staples for the purposes of the ReDD analysis. The others are vegetables, fruits, dairy foods, protein sources (including animal- and plant-based proteins), added fats, and discretionary foods (or added sugars).

Three features of the reference diet are worth noting. First, by setting ranges of intakes, Willet et al. (2019) acknowledge that food preferences differ and that some foods are substitutable, especially within major food groups. For example, vegetarians can substitute meat for plant-based proteins. For this reason, ranges for some food items start at zero, signifying that not all food items must necessarily be consumed to still have a healthy diet. Consuming more than the upper bound is acceptable for some foods such as vegetables, but upper bounds for others are considered thresholds that should not be exceeded. For example, calories from grain cereals should account for no more than 60 percent of daily calories, while discretionary foods should account for five percent or less of daily calories.

Second, Willet et al. (2019) also specify food group calorie amounts associated with the foods typically consumed in those food groups. These are derived roughly from the midpoints of the range of food quantities. When summed together, the diet provides a requisite 2,500 kilocalories per day, in this instance for a moderately active adult (requirements vary by age, gender, and physical activity). While the food group calorie amounts should not be interpreted as absolute thresholds that must be achieved, they provide a useful benchmark for an aspirational diet that yields enough daily calories derived from a diverse set of food groups, while also considering individual health and the global environment.

Table 1. Caloric intakes and cost of the EAT-*Lancet* healthy reference diet

Reference food intakes			Cost of a reference diet (2017 prices)			
Food groups	Intake & range (g/day)	Reference intake (kcal/day)	Reference item (lowest price, ICP)	ICP price (NGN/kcal)	Cost (NGN) (price x kcal)	Cost (PPP $)
1. Starchy staples		850			58.11	0.50
a) Grain cereals	232g (≤ 60% energy)	811	Maize grains	0.066	53.91	0.48
b) Root crops	50g (0–100g)	39	Fresh cassava	0.108	4.20	0.04
2. Vegetables	300g (200–600g)	78	Fresh carrots	0.699	54.53	0.49
3. Fruits	200g (100–300g)	126	Banana, short finger	0.338	42.61	0.38
4. Dairy foods	250g (0–500g)	153	Milk, fresh, unskimmed	0.315	48.13	0.43
5. Protein sources		726			114.11	1.02
a) Animal protein		151	Beef, minced	0.428	64.66	0.58
Beef and lamb	7g (0–14g)	15				
Pork	7g (0–14g)	15				
Poultry	29g (0–58g)	62				
Eggs	13g (0–25g)	19				
Fish	28g (0–100g)	40				
b) Legumes & nuts		575	Spotted beans	0.086	49.45	0.44
Pulses	50g (0–100g)	172				
Soy foods	25g (0–50g)	112				
Groundnuts	25g (0–75g)	142				
Tree nuts	25g	149				
6. Added fats		447	Palm oil unrefined	0.048	21.64	0.19
Palm oil	6.8 (0–6.8g)	57				
Unsaturated oils	40 (20–80g)	354				
Lard or tallow	5 (0–5g)	36				
7. Discretionary foods	31 (0–31g)	120	White sugar	0.155	18.58	0.17
Total		2,500			357.71	3.19

Source: Food intake levels (in grams and calories) based on Willet et al. (2019). Prices derived from World Bank (2020). Note: g = grams; kcal = kilocalories; ICP = International Comparison Program (World Bank 2020); PPP = purchasing power parity; NGN = Nigerian Naira.

Third, the first six major groups (as numbered in Table 1) are considered as required food groups, which means consumers should ideally consume foods from all these food groups, recognizing of course that (say) a vegan diet would exclude dairy products. Food items in the discretionary foods group are not considered required. If not consumed, calories from discretionary foods may be replaced by calories from other food groups. As we explain further below, the ReDD index is computed based on deprivation in the six required food groups in Table 1, i.e., whether calories are also obtained from discretionary foods is disregarded. However, discretionary foods are considered in the measurement of total food expenditure total calorie availability in the diet or.

2.3 Costing the reference diet

One area of criticism of the EAT-*Lancet* diet is its high cost to consumers. Hirvonen et al. (2020) find that the cost of the EAT-*Lancet* diet exceeds the (total) per capita expenditure of about one-quarter of the world population. This rises to 37 percent in lower-middle income countries and 62 percent in low-income countries. These findings are echoed in other studies on the cost of nutritious diets (Cost of Nutritious Diets Consortium 2018, Herforth, et al. 2020). Some have even questioned the usefulness of promoting a diet that is unattainable for so many people. Our perspective is that the reference diet is an aspirational diet, and while reducing the share of the population that cannot afford the overall diet is useful as a policy target, an even more important goal should be reducing the relative consumption gaps across all food groups.

Diet costing is an important element of our expenditure-based approach to measuring diet deprivation (ReDD-X). Whereas diet costing exercises have generally focused on the overall cost of healthy diets, the ReDD-X approach considers costs of (and expenditures within) each food group separately. The costing exercise broadly follows the method developed by Hirvonen et al. (2020). It entails identifying a reference food item within each food group (or subgroup) and multiplying its price (expressed in per calorie terms) by the reference calorie amount for that group. Price data are obtained from the International Comparison Program (ICP) global database, which records prices for over 400 food items from across 176 countries in 2017 (World Bank 2020). Among the developing countries in the ICP database, prices are reported for around 100–150 items in total and 10–30 items per food group. The price of the cheapest item in each food group is selected as a reference price, which is then multiplied by the reference calories. Table 1 demonstrates this using Nigerian prices in the ICP database (2017 prices). Note that within the staples group, costs are estimated separately for the cereals and roots subgroups before they are aggregated. The same applies for the protein foods, where animal- and plant-based proteins are costed separately before they are aggregated to the food group level. Only one reference item is selected for each of the remaining food groups.

Under this approach, the food group costs represent the lowest possible costs at which the reference calorie amounts can be acquired. Similarly, the total diet cost is the lowest cost at which a person can obtain 2,500 calories per day sourced from a diverse set of food groups. As shown in Table 1, summing across the food groups yields an overall reference diet cost in Nigeria of NGN 357.71 per person per day in 2017 prices, or USD 3.19 in purchasing power parity (PPP) terms. Survey data shows that 71.0 percent of Nigeria's population cannot afford the EAT-*Lancet* diet. By comparison, at the USD 1.90 international poverty line, Nigeria's poverty rate is 39.1 percent (World Bank 2021). This justifies concerns about the affordability of the EAT-*Lancet* diet. However, rather than focusing only on the share of people who cannot afford the diet, ReDD also considers the relative food consumption gap within food groups. This means even if a policy fails to reduce the share of people that are diet deprived, diets may still improve if food group consumption gaps decline.

2.4 Mathematical derivation

The method for computing the ReDD index is inspired by the Multidimensional Poverty Index (MPI) developed by Alkire and Foster (2011). The MPI is often used to study deprivation in non-monetary dimensions of wellbeing, such as education, health, or standards of living. The MPI uses a dual cut-off approach to identify the poor. At the first stage, for each dimension of wellbeing (e.g., education) a threshold (e.g., years of schooling) is defined, and any person below that threshold is considered deprived in that dimension. At the second stage, if an individual is deprived in more than a set number of dimensions—that number is a subjective choice—the person is considered multidimensionally deprived.

The six required food groups (Table 1) are used as the dimension in which deprivation is measured in the ReDD index. Since the analysis is based on survey data, the unit of observation is the household. If a household is deprived, every member of that household will also be considered deprived. In the case of ReDD-X, a household's per capita expenditure on a food group is compared against the reference cost of that food group to identify households that are deprived, while for ReDD-C, per capita calorie availability is compared against the calorie amount specified in the reference diet. Per capita expenditure or calorie amounts are obtained by dividing amounts reported at household-level by an adult equivalent household size measure, which accounts for varying calorie requirements of males and females of different ages.

Formally, we define x_{ij} as the expenditure (or calorie availability) for individual $i = 1, \dots, n$ on food group $j = 1, \dots, d$, and z as the vector of thresholds, with element z_j denoting the cost (or calorie) threshold for food group j. A matrix of normalized gaps g^{α} can now be defined for $\alpha = 0, 1$ or 2, where α is analogous to the parameter in the Foster-Greer-Thorbecke (FGT) class of poverty measures (Foster, Greer and Thorbecke 1984).

$$g_{ij}^{\alpha} = \begin{cases} \left(\frac{z_j - x_{ij}}{z_j}\right)^{\alpha} \text{ if } x_{ij} < z_j \\ 0 \text{ if } x_{ij} \geq z_j \end{cases} \qquad [1]$$

The first-stage identification considers a household and its members to be consumption-deprived in a food group if $x_{ij} < z_j$. Therefore, the deprivation matrix g^0 reduces to a function that takes on the value of one if the household is deprived in food group j and zero otherwise.

$$g_{ij}^{0} = \begin{cases} 1 \text{ if } x_{ij} < z_j \\ 0 \text{ if } x_{ij} \geq z_j \end{cases} \qquad [2]$$

Next, let w_j be the weight applied to food group j, with $0 < w_j < 1$ and $\sum_{j=1}^{d} w_j = 1$. Weights change the relative importance of deprivations in a food group in the measurement of overall deprivation. For example, sufficient consumption of starchy staples, an important source of inexpensive calories, may be considered vital in a context where energy-related undernutrition is widespread; or, sufficient consumption of vegetables, an important source of micronutrients, may be considered crucial in a context of widespread micronutrient deficiencies. If such motivations exist, larger weights can be attached to these dimensions or food groups. Since in the ReDD index we deem all required food groups equally important, the default is equal weights, i.e., $w_j = 1/d$.

Summing over the weighted deprivations yields a deprivation score c_i^0, which is used in the second-stage identification.

$$c_i^0 = \sum_{j=1}^{d} w_j . g_{ij}^0 \qquad [3]$$

For the second-stage identification we define the multidimensionally deprived as those suffering $k \in [1, \dots, d]$ or more deprivations, i.e., $c_i^0 \geq k/d$. The choice of k is subjective. A lower value of k will translate into a larger share of the population classified as multidimensionally deprived. As with dietary diversity scores (DDS), where there is no universal standard for what constitutes a low or high degree of diversity (Ruel 2003), there is no standard for what constitutes a low or high degree of deprivation. While one option is to report results for all values of k, we instead use $k = 1$ as the default, which is consistent with our assertion that each food group is required for a diet to be considered healthy. The second-stage identification function ρ_k takes on the value one if a household is deprived in k dimensions or more and zero otherwise.

$$\rho_k = \begin{cases} 1 \text{ if } c_i^0 \geq \frac{k}{d} \\ 0 \text{ if } c_i^0 < \frac{k}{d} \end{cases} \quad [4]$$

The ReDD index is a composite of several indicators, each with a unique interpretation. The first indicator is the headcount rate, H, which is the share of population that is multidimensionally deprived $(\rho_k = 1)$. In the equation below, q denotes the number of multidimensionally deprived people in the total population of n, which is obtained by summing over the second-stage identification function ρ_k. Since $k = 1$ and since very few people—even wealthy people in developing countries—follow the guidelines of a healthy reference diet, we expect the value of H to be close to one.

$$H = \frac{1}{n}\sum_{i=1}^{n}\rho_k = \frac{q}{n} \quad [5]$$

The second indicator is the intensity of deprivation, A. It measures the average deprivation share of the multidimensionally deprived and is computed by summing the censored deprivation score $c_i^0(k)$ over the subset of q multidimensionally deprived persons. The censored deprivation score, in turn, is derived from the censored deprivation matrix $g_{ij}^0(k)$, which is the product of uncensored deprivation matrix g_{ij}^0 and the second-stage identification function ρ_k.

$$A = \frac{1}{q}\sum_{i=1}^{q} c_i^0(k) = \frac{1}{q}\sum_{i=1}^{q}\sum_{j=1}^{d} w_j.\, g_{ij}^0\,(k) = \frac{1}{q}\sum_{i=1}^{q}\sum_{j=1}^{d} w_j.\, g_{ij}^0.\,\rho_k \quad [6]$$

An adjusted headcount ratio, M_0, can now be defined as the product of H and A.

$$M_0 = H.A = \frac{q}{n}.\frac{1}{q}\sum_{i=1}^{q} c_i^0(k) = \frac{1}{n}\sum_{i=1}^{n} c_i^0(k) = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{d} w_j.\, g_{ij}^0.\,\rho_k \quad [7]$$

For $\alpha = 1$ the normalized gap matrix g^1 takes on a value of $(z_j - x_{ij})/z_j$ if $x_{ij} < z_j$ and zero otherwise. The censored normalized gap matrix $g_{ij}^1(k)$ is the product of the uncensored normalized gap matrix and the second-stage identification function ρ_k. The adjusted deprivation gap measure, M_1, which is also our ReDD index, can now be defined as follows.

$$ReDD = M_1 = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{d} w_j.\, g_{ij}^1(k) = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{d} w_j.\, g_{ij}^1.\,\rho_k = H.A.G \quad [8]$$

ReDD can be expressed as the product of H, A, and G—the third indicator. H and A, as previously defined, measure the share of population that is multidimensionally deprived and the average number of deprivations suffered as a share of the total number of dimensions (or deprivation share). $G = M_1/M_0$ is the average deprivation gap across all food groups. The ReDD index can therefore be decomposed into components relating to the incidence (H), breadth (A), and depth (G) of multidimensional deprivation.

2.5 Comparing ReDD-X and ReDD-C

Although ReDD-X and ReDD-C are computed using the same survey data and similar mathematical methods, they measure different aspects of diets. ReDD-X considers food expenditure requirements if the cheapest calories were sourced. ReDD-C, on the other hand, is based on calorie availability in observed diets. This is an important distinction and has implications for how diet deprivation is interpreted under the two approaches. Under the expenditure-based approach, households who spend at or above the threshold would be considered not deprived, even though some of these households might not meet nutritional needs because they choose more expensive food items. In the cost-of-basic-needs poverty literature the classification of non-poor in this instance is still justified because the household is deemed to have the capability to meet basic needs (Arndt, Mahrt and Tarp 2017). The calorie-based approach, in contrast, considers calorie availability in the household, which brings the approach more in line with the use of context-specific poverty lines that are deemed consistent with revealed preferences. In contexts where the cheapest food items are unavailable due to location or seasonal factors, or where their consumption is avoided for dietary reasons, such an approach has merit.

Despite these differences, the ReDD-X and ReDD-C values estimated from the 2015-16 wave of the Nigeria General Household Survey – Panel Component (GHS-Panel 2015-16) are remarkably similar (Table 2) (Nigeria Bureau of Statistics & World Bank 2018). With respect to incidence of deprivation within food groups—i.e., the percentage of people with expenditure (or calories) below the food group cost (or calorie amount)—the biggest difference between ReDD-X and ReDD-C is observed for protein foods (79.7 versus 94.3 percent). This reflects a preference for more expensive meat or fish over beans as a source of protein in Nigeria. The values in brackets show the average food expenditure (or calorie availability) gaps at national level. The smaller calorie gaps in fruits and dairy foods may reflect that households access these foods at lower prices than those reported in the ICP database on which the cost thresholds are based (see section 0).

As expected, the headcount ratio (H) in both approaches is close to one, i.e., almost no Nigerian household achieves spending or calorie thresholds in all food groups simultaneously. To put this in perspective, however, we also find that 22.4 percent of households have food budgets that that exceed the total cost of the EAT-*Lancet* diet, while 56.6 percent access more than 2,500 kilocalories per adult equivalent (see last row in Table 2). Therefore, although all households are effectively multidimensionally deprived under either ReDD-X or ReDD-C, 22.4 percent could afford a healthy diet if they reallocated their food expenditures, while 56.6 percent consume enough calories, meaning they are not starving, they are just not consuming a healthy diet. The first percentage is relatively low because the reference diet is expensive and does not represent what people choose to consume. The second percentage is relatively high because most people get the bulk of their calories from cheap staples. Although mathematically these shares are defined in the same way, they measure very different aspects of diets in practice. The average deprivation shares (A) for ReDD-X and ReDD-C are 0.747 and 0.778, respectively, which means the average household suffers deprivation in roughly four or five out of six food groups. The average food consumption gap (G) under either approach is about two-thirds. Finally, the ReDD-X and ReDD-C estimates are 0.494 and 0.517.

Table 2. ReDD baseline estimates (2015/16)

	ReDD-X			ReDD-C		
	National	Urban	Rural	National	Urban	Rural
Food group deprivation rates (%)						
Starchy staples	11.6 (2.6)	9.6	12.6	13.2 (2.3)	19.6	10.0
Vegetables	91.1 (56.1)	87.3	93.2	95.9 (54.1)	96.9	95.4
Fruits	90.6 (73.8)	87.3	92.5	90.6 (58.1)	89.2	91.2
Dairy foods	98.6 (88.1)	98.0	98.9	97.1 (76.2)	95.3	98.0
Protein foods	79.7 (43.0)	71.1	84.5	94.3 (49.2)	94.7	94.1
Added fats	74.3 (32.7)	70.6	76.3	75.4 (27.8)	72.5	76.8
ReDD components (ratios)						
Headcount ratio (H)	0.995	0.992	0.997	1.000	1.000	1.000
Average deprivation share (A)	0.747	0.712	0.765	0.778	0.781	0.776
Average deprivation gap (G)	0.664	0.611	0.692	0.665	0.633	0.681
ReDD index	0.494	0.432	0.528	0.517	0.494	0.528
Share of deprived who can afford overall diet OR access enough total calories (%)	22.4	30.1	18.1	56.6	46.5	61.7

Source: Authors' estimates based on GHS-Panel 2015-16. Note: The top part of the table shows the incidence of deprivation within food groups—i.e., the percentage of people with expenditure (or calories) below the food group cost (or calorie amount)—at national level and for urban and rural populations. The values in brackets show the average food expenditure (or calorie availability) gaps at national level, or the average percentage shortfall in consumption among the deprived.

Although two approaches to measuring diet deprivation are proposed, we do not promote one over the other. Food expenditure data underlying the ReDD-X index are widely accessible, more easily processed, and arguably less prone to measurement error than the food quantities and calorie availabilities required for ReDD-C. Data quality is therefore a consideration when choosing among the two alternatives. Cost thresholds in ReDD-X, which are derived from World Bank (2020) prices, are also widely available, but these may not necessarily reflect the value of crops produced for those who rely on own consumption, or retail prices in local markets at the time purchases are made, even though the use of temporal and spatial deflators to adjust food expenditure in the household surveys attempts to correct for this. Its simplicity means ReDD-X is easily scaled to many countries and is therefore also the default diet indicator embedded in the RIAPA model (see section 2.7). However, in countries where good quality data is available, where there is an interest in assessing food consumption behavior, and a need to understand revealed dietary preferences in relation to reference diets rather than the attainability of least-cost diets, the ReDD-C approach may be preferred.

2.6 Correlation analysis

Although the ReDD index is a population-wide indicator, household-level deprivation is adequately represented by the following equation (compare equation [8] before summing over the population n).

$$ReDD_i = \sum_{j=1}^{d} w_j . g_{ij}^{1} . \rho_k \qquad [9]$$

Table 3 reports correlation coefficients between the two $ReDD_i$ variables and two commonly used diet quality indicators, the Dietary Deprivation Score (DDS) and the Food Variety Score (FVS), also in this instance measured at household-level and computed using the GHS-Panel 2015-16. For a description of the DDS and FVS computation, see Ecker & Hatzenbuehler (2021). Despite measuring different aspects of diet deprivation, ReDD-X and ReDD-C are strongly and positively correlated, with a correlation coefficient of 0.80 (this is also shown visually in the appendix, Figure A2). This suggests that food baskets of poor households tend to consist of cheaper calories as shaped by their poverty condition rather than tastes (Van den Boom, Halsema and Molini 2015). The implication is that a least-cost approach to measuring diet deprivation (i.e., ReDD-X) reasonably approximates a revealed preference approach (such as ReDD-C), and vice versa.

Table 3. Correlation coefficients: DDS, FVS, ReDD-X, and ReDD-C

	DDS	FVS	ReDD-X	ReDD-C
Dietary Deprivation Score (DDS)	1.00			
Food Variety Score (FVS)	0.82	1.00		
ReDD-X	-0.52	-0.53	1.00	
ReDD-C	-0.44	-0.47	0.80	1.00

Source: Authors' estimates based on GHS-Panel 2015-16.

As hypothesized previously, the ReDD index indirectly measures diet quality in that it incorporates elements of both nutrient (in)adequacy and (a lack of) dietary diversity. Dietary diversity scores such as DDS and FVS are known to be positively correlated with diet quality. As we show in Table 3, ReDD-X and ReDD-C are moderately and negatively correlated with DDS and FVS, thus confirming the expected inverse relationship. The inverse relationship is marginally stronger for ReDD-X than for ReDD-C.

2.7 ReDD and overconsumption

With the growing problem of overweight and obesity, the overconsumption of calories, sourced especially from refined grains, highly processed foods, and added sugars is as much a concern as undernutrition and micronutrient deficiencies. As a deprivation measure, the ReDD index only measures consumption deficits, while households with excess consumption ($x_{ij} \geq z_j$) are simply considered to have adequate diets. This requires further consideration.

Although z_j is treated as an explicit threshold in the calculation of ReDD, reference diets such as the EAT-*Lancet* diet typically propose ranges of caloric intakes for each food group (Table 1). In principle, the normalized gap matrix in equation [1] could be modified to identify both those households that are below a lower-bound threshold, z_j^l, and above an upper-bound threshold, z_j^u.

$$g_{ij}^{\alpha} = \begin{cases} \left(\frac{z_j^l - x_{ij}}{z_j^l}\right)^{\alpha} \text{ if } x_{ij} < z_j^l \\ \left(\frac{x_{ij} - z_j^u}{z_j^u}\right)^{\alpha} \text{ if } x_{ij} > z_j^u \\ 0 \text{ if } z_j^l \leq x_{ij} \leq z_j^u \end{cases} \quad [13]$$

While this is intriguing, such an approach has several disadvantages. Firstly, it would complicate the interpretation of the average deprivation gap measure, G, which would now combine under- and overconsumption gaps. Secondly, while this approach would be feasible with a calorie-based approach (ReDD-C), it will fail to distinguish between households that overconsume calories or simply choose expensive foods in the expenditure-based approach (ReDD-X). Thirdly, whereas minimum calorie thresholds based on moderate physical activity provide a plausible lower-bound for the entire population, high calorie intakes may be healthy or even necessary for highly active or larger people. Lastly, when applied in a simulation setting (see section 3.3), a variant of the ReDD index that combines under-consumption and overconsumption may produce results that are difficult to interpret. For example, a policy that reduces the cost of starchy staples would allow hungry people to narrow their under-consumption gap, but it might equally encourage those that over-consume to consume even more, resulting in ambiguous effects on the overall diet quality measure. Thus, while we acknowledge this limitation in of the ReDD index, combining under- and overconsumption in this indicator does not appear to be sensible.

3 Modeling the impact of agricultural development on Nigerian diets

3.1 The RIAPA model

The Rural Investment and Policy Analysis (RIAPA) model and data system developed by the International Food Policy Research Institute (IFPRI) is a simulation laboratory for conducting forward-looking, economywide analysis. At the core of RIAPA is a recursive-dynamic computable general equilibrium (CGE) model that captures the linkages and market interactions between producers and consumers. Outside of the core model, various RIAPA input modules are used to refine model simulations, while RIAPA output modules produce specialized outcomes indicators, e.g., on agri-food system growth, employment and other labor market outcomes, poverty, inequality, and now, diet deprivation.

The CGE model inside the RIAPA system adopts all the common features of standard, single-country CGE models, including multi-level nested production functions, imperfect substitution between domestic and imported commodities, and a linear expenditure system of consumer demand. Details are provided in Diao and Thurlow (2012). Various closure rules define the market clearing mechanisms in the model. For the analysis in this paper, we assume full factor mobility for workers and agricultural land, while capital is activity specific. Wage, land, and capital rates adjust to maintain full employment, while factor supply growth rates follow historical trends. The government closure assumes fixed tax rates and flexible government savings. Private savings are fixed as a proportion of income. Aggregate (private and public) savings determine the level of investment under a savings-driven investment closure. The external balance is maintained through a flexible exchange rate that adjusts to clear the capital account.

Several unique features make RIAPA an ideal policy analysis and decision-making tool. First, its detailed structure allows measurement of impacts within and across numerous food value chains captured in the model, including on primary production, food trade and transport, processing, and food services. The economywide structure means linkages between the agri-food system and the broader economy are also captured. Second, RIAPA highlights trade-offs associated with policy choices given competition over scarce resources, structural differences between sectors, and differences in the way households participate in the economy. This allows policymakers to better appreciate the intended and unintended consequences of policy actions. Third, by incorporating survey-based output modules, RIAPA allows for a more nuanced assessment of distributional and welfare effects of policy or investment choices. Increasingly, policymakers are expected to prioritize among policies based on purely economic and socio-economic outcomes, and the diverse set of outputs and indicators produced by the RIAPA model can inform those decisions.

3.2 Nigeria model and data

The RIAPA model is calibrated to a 2018 SAM for Nigeria (Thurlow 2021). The macro-accounts in the SAM are consistent with Nigerian national accounts data. IFPRI's standard Nexus SAM structure includes 15 representative household groups, disaggregated by per capita expenditure quintile, and split into rural farm, rural nonfarm, and urban households. It also defines 90 activity accounts, 46 of which produce food commodities consumed by households. This includes food commodities produced by the primary agricultural sector, including 23 crop, 6 livestock, and 2 fisheries subsectors, as well as 15 food commodities produced by the food processing sector.

RIAPA simulations generate results on consumption choices and real food price changes for 15 household types and the 46 food items, all within an internally consistent and comprehensive economywide framework. Simulation results on consumption and price changes inform changes in diet cost and diet deprivation (the methods are described in the next section). To achieve this, RIAPA food commodities are mapped to the reference diet food groups, as shown in the appendix, Table A1. Two points are worth highlighting. First, included in the 46 RIAPA food commodities are 8 commodities that are mapped to the discretionary food group. Since discretionary foods are excluded from our definition of deprivation, only expenditure and prices of the remaining 38 RIAPA food commodities directly affect the ReDD index. Second, each reference diet food group is associated with several RIAPA commodities. Thus, even if the ReDD index only considers deprivation across 6 food groups, RIAPA models substitution among food items within those groups.

3.3 Modeling changes in diet quality

The diet module is a survey-based microsimulation module linked sequentially to the RIAPA model. RIAPA simulation results can be compared against a counterfactual (i.e., the baseline), or changes in economic variables can be tracked over time given the recursive-dynamic setup of the model. For the diet module, simulated changes in real food expenditures and prices in RIAPA are linked to households in the underlying household survey, in this instance the Nigeria GHS-Panel 2015-16. A microsimulation model then assesses changes in diet deprivation status of households and computes changes in the ReDD index. As we elaborate below, two algorithms have been developed to accommodate the computation of ReDD-X and ReDD-C. Figure A1 (appendix) is a graphical representation of these approaches.

3.3.1 Expenditure-based approach

Following the notation from section 2.4, changes in ReDD-X can be due either to changes in food group expenditures (x_{ij}) or changes in reference diet costs (z_j). The RIAPA model produces results on changes in food expenditure incurred by 15 representative household groups (h) on 38 food items (c) linked to reference food groups, as well as price changes for each of the food items. The objective of the ReDD-X algorithm is to map RIAPA expenditure changes to households in the survey to compute new household food group expenditure values (x_{ij}^*). The algorithm also maps price changes to a diet costing equation to compute new reference diet costs (z_j^*). This allows us to compute changes in ReDD-X over time or those associated with a simulation shock.

RIAPA food expenditure results are first aggregated to food group level $(c \rightarrow j)$. Next, households—and by extension their members—in the survey are mapped to their representative household groups in RIAPA $(i \rightarrow h)$. The percentage change in food expenditure $(\Delta x_{ij}/x_{ij})$ is derived directly from RIAPA food group expenditure results by assuming that each survey household experiences the same percentage change in consumption as its representative household group.

It is not uncommon for survey households to report zero food expenditure for certain food groups. This may truly reflect non-consumption (e.g., a vegan household choosing not to consume dairy products), but it often reflects forgetfulness of survey respondents or the fact that short survey recall periods are associated with underreporting of less frequently consumed foods (e.g., meat) or seasonal foods (e.g., fruit). For example, in Nigeria (GHS-Panel 2015-16), 30–40 percent of households report no expenditure on fruit and dairy products. For this reason, we apply the consumption change to a latent food expenditure value ($\hat{x}_{ij}$) instead of the observed food expenditure value to compute post-simulation food expenditure values.

$$x_{ij}^{*} = \left(\frac{\Delta x_{ij}}{x_{ij}}\right) . \hat{x}_{ij} + x_{ij} \qquad [10]$$

The latent expenditure value reflects a household's long-term average consumption, given income and other household characteristics. These are predicted from regression models on observed budget shares. For food groups where fewer than five percent of households report zero consumption, ordinary least squares models are used. If five percent or more respondents report zero-consumption, we assume the selection into the subsample of non-consuming households is nonrandom, and a Heckman two-step selection model is used. The choice of five percent is arbitrary. In both models, independent variables include the logarithm of food expenditure, the age and education of the household head, and dummy variables identifying administrative regions, rural locations, and farming households.

The next step is to adjust diet costs (z_j). Prices in the RIAPA model are expressed relative to a fixed numeraire, typically a price index such as the producer or consumer price index that is representative of a basket of food and nonfood items. Diet costs are constructed from food prices only and may therefore change relative to the model numeraire. We use the mapping between RIAPA food commodities and food groups ($c \rightarrow j$) to compute a consumption-weighted national average price change $\left(\Delta p_j / p_j\right)$ for each major food group that is consistent with price changes observed in RIAPA. New cost thresholds $\left(z_j^{*}\right)$ can now be computed by applying the price change to the baseline diet cost.

$$z_j^{*} = \left[1 + \left(\frac{\Delta p_j}{p_j}\right)\right] . z_j \qquad [11]$$

Once new diet cost thresholds $\left(z_j^{*}\right)$ and household expenditures $\left(x_{ij}^{*}\right)$ have been estimated for each household, new ReDD-X values can be computed. The ReDD-X algorithm also produces results on H, A, and G, and the share of diet deprived households that can afford a healthy diet (compare Table 2).

3.3.2 Calorie-based approach

There are several key differences between the ReDD-C and ReDD-X algorithms. Since ReDD-C is a calorie-based measure, estimates of baseline calorie availability $\left(x_{ij}\right)$ in the survey are obtained by multiplying the edible portion of reported food quantities by calorie contents. For Nigeria we use calorie conversion factors by Stadlmayr et al. (2012). Reference diet thresholds are also expressed in calorie terms which are independent of prices and therefore fixed at baseline levels in all simulations ($z_j = z_j^{*}$). Thus, in linking the microsimulation model to RIAPA results, we only need to consider changes in calorie availability and not in the reference diet thresholds.

Another key difference in the ReDD-C algorithm is the use of econometrically estimated income and price elasticities to compute post-simulation calorie availability amounts (x_{ij}^{*}). A complete food demand system is estimated to produce income and price elasticities. The estimation strategy comprises two stages. At the first stage a Working-Leser (WL) model is used to produce elasticities of demand for aggregate food and nonfood consumption (Working 1943, Leser 1963). This model describes households' budget allocation across aggregate food and nonfood items. At the second stage the household allocates its food budget across individual food groups. The within-food budget allocation is modeled using a censored quadratic almost ideal demand system (QUAIDS) that allows for full substitutability between foods, conditional on the available food budget, and controls for household economies of scale and seasonality in food consumption (Banks, Blundell and Lewbel 1997). The censored QUAIDS uses latent food budget share equations that are estimated in a two-step procedure to account for the presence of zero food consumption observations (Shonkwiler and Yen 1999). For a detailed description of the demand system estimation, see Ecker and Comstock (2021). Summary income and price elasticity results are reported in the appendix (Table A2).

The food demand system for Nigeria is estimated by making use of the seasonal panel structure of the GHS-Panel 2015-16 data and, to reduce potential endogeneity problems, by instrumenting income and expenditure variables with the corresponding variables from the previous survey wave in 2012-13. Income (or expenditure) elasticities ($\in_{ij}^{y}$) are estimated for 15 food groups (f) (see Table A2) and ten household groups (s) (rural and urban quintiles) before they are mapped to the broader food groups ($f \rightarrow j$) and individual households ($i \rightarrow s$) in the survey. Note these same elasticities are used to calibrate the demand system in the CGE model. The percentage change in the food budget ($\Delta y_i / y_i$) is derived from RIAPA results. The food budget is the sum of expenditure across the RIAPA food commodities (c). The percentage change in the food budget for each representative household group in RIAPA is then mapped to survey households ($i \rightarrow h$), like the approach in mapping food group expenditures in the ReDD-X algorithm.

Own-price elasticities ($\in_{ij}^{p}$) are similarly estimated for 15 food groups (f) and ten household subgroups (s) and then mapped to individual households. A household-specific price change $\left(\Delta p_{ij}/p_{ij}\right)$ is derived from RIAPA results. This measures, for each RIAPA representative household group (h), the weighted average price change within a food group (j) considering the household group's unique basket of food commodities within that food group ($c \rightarrow j$). Price changes for representative household groups are then mapped to the individual households ($i \rightarrow h$) in the survey.

The equation below shows how the percentage change in calorie availability $\left(\Delta x_{ij}/x_{ij}\right)$ is computed. The two terms on the right-hand side represent the income and price effects, respectively.

$$\left(\frac{\Delta x_{ij}}{x_{ij}}\right) = \left[\in_{ij}^{y} \cdot \left(\frac{\Delta y_i}{y_i}\right)\right] + \left[\in_{ij}^{p} \cdot \left(\frac{\Delta p_{ij}}{p_{ij}}\right)\right] \qquad [12]$$

Consistent with the approach adopted in the ReDD-X algorithm—see equation [10]—consumption changes are applied to a latent calorie availability value ($\hat{x}_{ij}$) to avoid issues associated with zero (or missing) food consumption. Latent calorie availability amounts are derived from the latent food budget shares predicted from the QUAIDS model parameters. The new calorie availability amounts $\left(x_{ij}^{*}\right)$ are now compared against the (fixed) calorie thresholds $\left(z_j^{*}\right)$ to compute new ReDD-C index values.

Note, the use of an econometrically estimated demand system, while novel, is optional. A simpler hybrid approach may entail directly estimating calorie availability from simulated changes in food consumption quantities in RIAPA. However, such an approach may not capture substitution of individual food items within food groups—this may influence the calorie contents of aggregate food groups—at the same level of detail as in the microsimulation model.

4 Simulation setup and results

4.1 Simulation setup

RIAPA serves as a simulation laboratory for experimenting with different policy and investment scenarios or external shocks and assessing their implications for sectoral production, household incomes, and market prices. We conduct hypothetical agricultural value chain productivity growth scenarios to showcase the features of the diet module. The choice of scenarios also highlights the potential of productivity-enhancing, sector-specific agricultural investments in changing food environments and diets through their impacts on food supply, household incomes, and relative food prices, even though we do not explicitly consider the source or cost of achieving that productivity growth. The analysis focuses on 11 agricultural value chains in Nigeria, namely (1) maize, (2) rice, (3) traditional grains (mainly sorghum and millet), (4) root crops (mainly cassava and yam), (5) vegetables, (6) fruits, (7) pulses and groundnuts, (8) dairy, (9) red meat (beef, goat, and sheep), (10) poultry and eggs, and (11) fish (including aquaculture and capture fisheries). These cover the spectrum of subsistence and commercial food value chains in Nigeria.

A baseline scenario assumes a continuation of the historical level and structure of growth over a simulation period spanning 2020–2025. Baseline GDP grows from NGN 127 to 155 trillion over the simulation period, or at 4.02 percent per annum (Table 4). In each of the value chain scenarios, total factor productivity in the targeted value chain is increased by enough to generate an additional NGN 519 billion in GDP over the simulation period relative to the baseline. Considering the overall size of the economy, this is a small change, and results in annual GDP growth increasing marginally to 4.04 percent in each value scenario. The objective is not to identify sources of growth, but to compare the effectiveness of GDP growth originating within targeted value chains on diets. By normalizing the marginal GDP effect across scenarios, the size effect of some agricultural subsectors is neutralized, and the scenarios are broadly comparable in the sense that they generate similar increases in national household income.

Of course, normalization also means smaller value chains need to grow faster than larger ones to achieve the same increase in overall GDP. As shown in Table 4, the poultry and eggs sectors make up only 0.3 percent of total GDP, and so TFP growth needs to be raised by 3.5 percentage points above baseline growth to generate an additional NGN 519 billion over the simulation period. By contrast, the incremental TFP growth rate in the larger root crops sector required to generate the same amount of additional GDP is only 0.2 percentage points above baseline.

Table 4. Simulation setup and simulated GDP impacts, 2020–2025

	Avg. baseline growth (%)	Simulations: Deviation from baseline GDP growth during 2020–2025 (%-point)										
		Maize	Rice	Trad. grains	Root crops	Veg.	Fruits	Pulses & g'nuts	Dairy	Red meat	Poultry & eggs	Fish
Simulated productivity growth		1.01	0.69	1.38	0.15	0.31	0.70	0.80	3.27	0.76	3.54	1.63
Initial GDP share of growth sectors		1.04	1.42	0.78	9.17	4.95	1.63	0.74	0.33	1.31	0.29	0.65
GDP growth	4.02	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Agriculture	2.84	0.089	0.076	0.090	0.090	0.067	0.078	0.103	0.076	0.065	0.073	0.036
Crops	*2.81*	*0.101*	*0.086*	*0.103*	*0.102*	*0.075*	*0.088*	*0.117*	*-0.004*	*-0.005*	*-0.008*	*0.020*
Livestock	*2.81*	*0.006*	*-0.002*	*-0.002*	*-0.003*	*0.001*	*-0.002*	*-0.004*	*0.979*	*0.859*	*0.987*	*0.002*
Other	*3.67*	*-0.006*	*0.011*	*-0.004*	*-0.002*	*0.008*	*0.001*	*-0.008*	*-0.005*	*-0.001*	*-0.003*	*0.457*
Industry	3.90	0.000	0.002	-0.003	-0.003	0.002	0.001	-0.007	0.001	0.003	0.000	0.009
Agroprocessing	*4.63*	*0.026*	*0.024*	*-0.004*	*-0.004*	*0.012*	*0.006*	*0.049*	*0.051*	*0.000*	*-0.001*	*0.021*
Services	4.48	0.000	0.003	0.000	0.001	0.007	0.003	-0.002	0.004	0.007	0.005	0.014

Source: RIAPA model results.

4.2 Macroeconomic results

Table 4 reports average GDP growth rates during 2020–2025 in the baseline as well as deviations from baseline growth in the value chain scenarios. As discussed, all value chain scenarios, by design, have the same marginal impact on national GDP (0.017 percentage points). The additional growth is concentrated in the agricultural sector, although productivity growth in value chains with larger off-farm components (e.g., commercially oriented value chains or those that are more likely to be processed, such as vegetables, meat, or fish) have a noticeable impact on growth in the industrial or services sectors. Within the agricultural sector, the incidence of growth on the crops, livestock, or fisheries subsectors depends largely on the value chains targeted (see highlighted cells in Table 4).

Competition for resources is an important feature of the RIAPA model. When productivity is raised in the targeted value chain, it lowers production costs and prices, raises demand, thus creating incentives to increase output. The resulting competition for land and labor inputs negatively affects other value chains. For example, when productivity is raised in crops value chains, livestock GDP declines. Competition also explains the small but economically significant differences in agroprocessing GDP across the scenarios. In general, agroprocessing benefits from increased agricultural productivity because of a decline in intermediate input costs. However, when productivity is raised in value chains associated with minimal processing (e.g., traditional grains, root crops, or poultry and eggs), it attracts resources away from value chains with larger processing components (e.g., dairy, oilseeds, or rice), resulting in a decline in overall economic activity—and value addition—in the agroprocessing sector.

4.3 Food costs and consumption

Table 5 reports diet costs in the baseline in 2025 as well as deviations from baseline in the various value chain scenarios. Diet costs are expressed in local currency (NGN) and deflated to 2015-16 prices to match the GHS-Panel 2015-16 survey period. The total cost estimate here also excludes the cost of discretionary foods, which explains the lower costs in Table 5 compared to those previously reported in Table 1.

Agricultural productivity gains reduce the overall cost of a healthy diet across all scenarios except the root crop scenario. These are real costs, expressed relative to a fixed numeraire in the model. As expected, declines in diet costs are driven largely by price declines in food groups directly linked to the targeted value chains. For example, the cost of staples declines in the maize, rice, and traditional grains value chain scenarios. However, it is also evident that costs of food groups not linked to the targeted value chains often increase. For example, in the vegetable scenario, the cost of the vegetable food group declines 2.28 percent, but costs of all other food groups increase. This again reflects competition for resources in the agricultural sector, i.e., higher demand for land and labor inputs in expanding sectors raise rents and wages, which in turn raise production costs in those sectors that do not experience productivity gains. This highlights the importance of using an economywide framework when conducting comparative value chain analysis.

The root crop scenario is an anomaly as far as diet costs are concerned. Not only does growth in this value chain cause the overall cost of a healthy diet to increase, but costs also increase for staples, of which root crops is a part. Further disaggregation of the price effects (not shown in Table 5) reveals that root crop prices indeed decline in the root crop scenario, as expected, but a rise in cereals prices—once again because of competition for land and labor inputs—dominates, causing the overall cost of staples to rise. Root crops are widely consumed in Nigeria, contributing 22 percent of calories in an average diet. This is less than the 44 percent that come from cereals, but these consumption shares are very different from those in the reference diet, which allows for only 2 percent of calories from root crops (30 kilocalories) and 32 percent from cereals (811 kilocalories) (see Table 1). If observed consumption shares were used as weights in the computation of an average cost of staples, the price would have declined. Instead, the cost in the reference diet is calculated using the reference diet consumption weights. With these relative calorie weights, the price decline in roots is simply not enough to offset the effect of rising cereal prices on the cost of staples in the reference diet.

Scenarios that stand out in terms of their food price impacts are the fruit (-4.19 percent) and dairy (-11.35 percent) scenarios. Both these value chains are characterized by limited demand from processors or final consumers. For example, the average Nigerian diet includes only 40 percent of the calories recommended by the EAT-*Lancet* diet for fruit and 18 percent for dairy foods. These value chain scenarios therefore have a strong impact on the affordability of the reference diet, but they do not necessarily lead to a strong demand response. Sharp price declines also discourage new entrants in these value chains. Any growth strategy targeting sectors with these characteristics should, ideally, simultaneously address demand side constraints.

Table 6 reports on food consumption gaps. The first column shows the percentage of people that are deprived in each food group in the baseline scenario by 2025. Consistent with the ReDD-X approach, a household (and its household members) is considered deprived if its expenditure is below the reference diet costs for a food group. The second column shows the average deprivation gaps, i.e., the percentage shortfall in consumption among deprived households. Compared to the initial deprivation rates in Nigeria (see Table 2), we notice an appreciable decline in deprivation rates over the simulation period in the baseline, although average deprivation gaps for those that remain deprived do not change as much.

Table 6 also reports the deviation in deprivation gaps from the baseline in percentage points terms. As expected, average consumption gaps decline in those food groups associated directly with the targeted value chains. For example, the vegetable consumption gap declines 1.33 percentage points in the vegetable scenario. However, in all scenarios we also see increases in consumption gaps in food groups not directly linked to the targeted value chains as households reallocate expenditure away from food groups for which costs increase (see Table 5). The effect of the value chain growth scenarios on overall diet quality is therefore ambiguous. This illustrates the value of the ReDD index, which considers the multidimensional nature of diet quality. Of course, when household incomes rise substantially—this is not the case in these scenarios—income effects may dominate substitution effects.

Table 5. Simulated diet costs by 2025

	Baseline diet cost (NGN) (2025)	Simulations: Deviation from baseline diet cost in 2025 (%)										
		Maize	Rice	Trad. grains	Root crops	Veg.	Fruits	Pulses & g'nuts	Dairy	Red meat	Poultry & eggs	Fish
Total cost	282.58	-0.103	-0.085	-0.067	0.120	-0.256	-0.417	-0.880	-2.121	-0.671	-0.682	-0.376
Staples	47.20	-0.921	-0.755	-0.941	0.049	0.098	0.144	-0.072	-0.054	0.136	0.149	0.046
Vegetables	46.18	-0.048	-0.100	0.072	0.090	-2.279	0.095	-0.316	0.154	0.118	0.146	-0.036
Fruits	35.88	0.071	0.033	0.109	0.130	0.120	-4.190	0.011	0.173	0.126	0.137	-0.013
Dairy	42.09	0.116	0.179	0.130	0.164	0.212	0.158	0.140	-11.345	-0.977	-0.916	0.170
Protein foods	94.49	0.069	0.058	0.110	0.137	0.127	0.126	-2.163	-1.455	-1.778	-1.864	-1.214
Added fats	16.73	0.154	0.124	0.142	0.174	0.183	0.172	-1.942	0.289	0.178	0.190	0.068

Source: RIAPA model results. Note: NGN = Nigerian Naira. Diet costs are expressed in 2015/16 prices to match the GHS-Panel 2015-16 survey year. The total cost estimate excludes the cost of discretionary foods. This explains the lower costs compared to those in Table 1, which are in 2017 prices and include discretionary foods.

Table 6. Food consumption deprivation and gaps by 2025

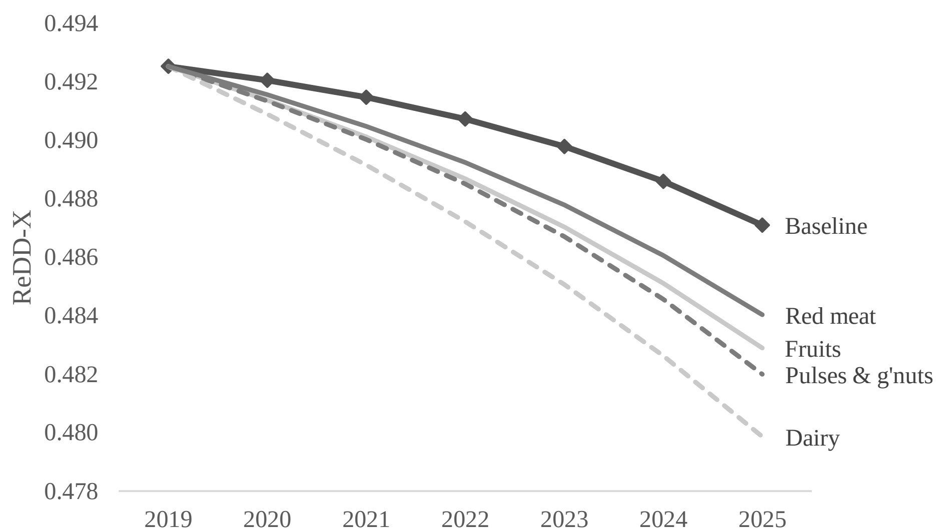
	Baseline (2025)		Simulations: Deviation from baseline consumption gap in 2025 (%-point)										
	% of pop. deprived	Avg. cons. gap	Maize	Rice	Trad. grains	Root crops	Veg.	Fruits	Pulses & g'nuts	Dairy	Red meat	Poultry & eggs	Fish
Staples	9.84	2.18	-0.173	-0.125	-0.196	-0.041	0.001	0.016	-0.043	-0.011	0.015	0.018	-0.001
Vegetables	92.00	57.37	-0.042	-0.082	0.023	0.023	-1.325	0.030	-0.211	0.057	0.045	0.061	-0.049
Fruits	90.89	73.29	0.013	-0.030	0.031	0.025	-0.001	-2.740	-0.057	0.046	0.035	0.042	-0.061
Dairy	98.82	88.96	0.015	0.023	0.018	0.019	0.023	0.020	0.009	-3.243	-0.239	-0.226	0.019
Protein foods	80.60	43.05	0.032	0.019	0.056	0.060	0.047	0.060	-1.302	-1.356	-1.796	-1.781	-0.744
Added fats	68.65	27.40	0.093	0.052	0.081	0.087	0.080	0.093	-1.458	0.166	0.100	0.108	0.010

Source: RIAPA model results. Note: Deprivation status and consumption gaps are based on food expenditures and reference diet cost thresholds, consistent with the ReDD-X index. A similar analysis could be conducted for calories (ReDD-C). As shown in Table 2, deprivation measures based on expenditures and calories are very similar.

4.4 <u>Diet outcomes</u>

Figure 1 shows the change in ReDD-X over time in the baseline and in the four value chain scenarios identified as having the largest impact on ReDD-X per unit of GDP growth, namely the dairy, pulses and groundnuts, fruits, and red meat value chains. All scenarios have the same starting point in 2019, with a ReDD-X value of 0.493. ReDD-X declines 0.005 points over the simulation period, reaching 0.487 in 2025. The decline in ReDD-X is accelerated in the selected value chain scenarios, with the strongest impact in the dairy value chain. In this scenario, ReDD-X declines 0.013 points to reach 0.480 in 2025. This is 0.007 points below the comparative value in the baseline in 2025.

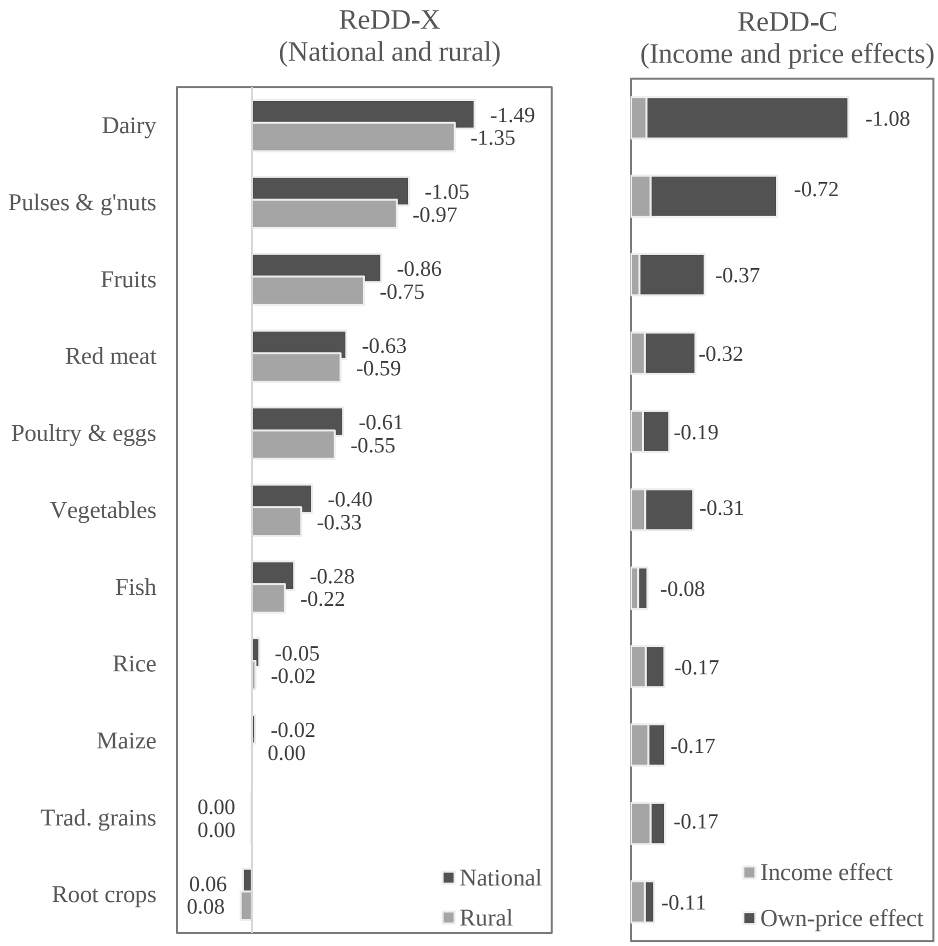
Figure 1. Changes in ReDD-X over the simulation period, 2020-2025



Source: RIAPA model results.

Figure 2 reports the changes in ReDD-X and ReDD-C from baseline in 2025, now in percentage terms. The ReDD-X panel (left) includes results for the whole population and for rural households. ReDD-X declines in all the scenarios except traditional grains (no change) and root crops (increase). The deterioration of diets in the root crop scenario relates to the increase in overall diet cost (see Table 5). For the remaining scenarios, the decline in ReDD-X is consistently smaller for rural households than for urban ones, who see some of their income gains from increased agricultural output eroded by lower food prices.

Figure 2. Comparison of ReDD-X and ReDD-C, deviation from baseline (%) in 2025



Source: RIAPA model results.

The ReDD-C results are broadly consistent with the ReDD-X results in terms of the ranking of value chains, although the changes from baseline, in percentage terms, are slightly smaller. Notable differences include the result for vegetables (ranked ahead of poultry and eggs) and fish (ranked last). Since the ReDD-C algorithm measures both income and price effects, the total effect can be decomposed. Income effects are similar across the scenarios because all scenarios have the same impact on national GDP and therefore very similar impacts on national household income. The differences that remain relate to differences in income elasticities and household income distribution between scenarios. Price effects dominate, especially in the higher-ranked value chains.

4.5 ReDD and other development outcomes

As shown in the preceding section, the ReDD index is useful for comparing and ranking value chains based on their impacts on diets. ReDD-X is now a standard outcome indicator in RIAPA for tracking diet outcomes associated with any set of policies or investments. Where data and resources permit, a ReDD-C analysis and the accompanying demand system analysis can also be undertaken. In addition to diets, RIAPA can also track outcomes in several other development indicators, including, for example, poverty, inequality, growth, or employment. Because of the opportunity costs of public spending, competition for scarce resources, and structural differences across sectors, not all policies will be equally effective at improving all development outcomes. How policymakers prioritize across policies or investments ultimately depends on the relative importance that governments or societies attach to different development outcomes.

RIAPA can inform these prioritization decisions. Figure A3 (appendix) shows a value chain ranking for Nigeria based on a composite score derived from three development indicators. The first is a poverty-growth elasticity that measures the percentage-point change in national poverty per unit of agricultural GDP growth; the second is a measure of agricultural transformation, i.e., the percentage change in agri-food system GDP per unit of growth in agricultural GDP; and the third is a diet elasticity that measures the percentage-point change in the ReDD-X index per unit of agricultural GDP growth (consistent with earlier results). All elasticities are normalized to range from zero to one, with one denoting the strongest effect. In the example shown, we assume policymakers weight poverty, growth, and diet outcomes equally. The ranking may be different if a different set of importance weights were used.

As noted previously, these scenarios do not consider the source or cost of achieving productivity growth in a value chain. The value of this type of analysis lies in demonstrating how value chains, because of their unique structural features (i.e., inter-industry linkages, employment patterns, and supply of consumer goods), differ in terms of the development outcomes they can bring about. It is therefore useful as a value chain prioritization exercise. Of course, the cost of achieving productivity growth differs from one value chain to the next. A next step would be to consider the types of policies or investments that could bring about productivity growth in value chains, to conduct a detailed costing exercise of those policies, and to simulate the effects of those policies on development outcomes per dollar spent. When several such policies are considered alongside one another, the analysis becomes useful as a policy prioritization exercise. This is a nontrivial exercise and falls beyond the scope of this analysis.

5 Conclusions

Poor diet quality, as it relates to deficiencies, excesses, or imbalances in people's energy or nutrient intakes, is recognized as one of the leading causes of malnutrition and non-communicable diseases. As a result, there is growing interest among policymakers to better understand the drivers of dietary change. Food environments are shaped by consumers' personal circumstances, norms, markets, and policies, which in turn are intrinsically linked to food supply chains that encompass production, storage, processing, and marketing of food. The complexity of the food system provides many entry points for policymakers to directly influence diets. Dietary change may also be a byproduct of other policies or investments due to their impacts on household incomes or relative food prices.

The objective in this paper is two-fold. The first is to introduce a new diet quality measure that can be computed from standard household consumption and expenditure data and measures diet quality in relation to a reference diet that specifies benchmark food intakes for major food groups. Our Reference Diet Deprivation (ReDD) index is a compound measure of the share of the population that is deprived in one or more food groups (incidence of deprivation), the average number of food groups in which consumers are deprived (breadth of deprivation), and the average gap between observed and threshold consumption levels (depth of deprivation). As such, it captures multiple dimensions of diet deprivation in one indicator. The index can be computed either using food expenditure or calorie availability data.

The second is to showcase an approach for integrating the ReDD index into an economywide model framework, in this instance the Rural Investment and Policy Analysis (RIAPA) model. As a continuous, quantifiable variable that is sensitive to marginal changes in household incomes and relative food prices, the ReDD index is ideally suited for use in an economic model. ReDD can help policymakers understand the likely impacts of policies, investments, or external shocks on household diets. In addition to the ReDD index, RIAPA also tracks other development indicators, such as poverty, inequality, economic growth, or employment.

We use the RIAPA model as a simulation laboratory for comparing the effectiveness of productivity growth in different agricultural value chains in Nigeria on diet outcomes. A baseline scenario assumes a continuation of the historical level and structure of growth over a simulation period spanning 2020–2025. Outcomes under 11 agricultural value chains—maize, rice, traditional grains, root crops, vegetables, fruits, pulses & groundnuts, dairy, red meat, poultry & eggs, and fish—are compared against the baseline. In each scenario, total factor productivity grows by enough to generate an additional NGN 519 billion in GDP over the simulation period relative to the baseline. Although this is a small change, the objective is not to identify sources of growth, but to compare the effectiveness of growth originating within targeted value chains on diets. By normalizing the GDP effect, scenarios are made to be broadly comparable in that they generate similar increases in national household income.

The dairy, pulses, fruit, and red meat value chains emerge as most effective at improving diet quality relative to the baseline over the simulation period. This ranking is robust to the choice of diet indicator, i.e., the expenditure-based ReDD-X or the calorie-based ReDD-C. Since agricultural productivity gains are often associated with falling food prices, urban household incomes grow more than those of rural households (and especially farm households), resulting in slightly weaker improvements in diet quality in rural areas. However, simulated income changes are relatively small by design, and as such relative price changes dominate the effect on ReDD. Under scenarios where the impact on relative prices is neutral and where income changes are more substantial, income effects may dominate.

The ReDD index has some drawbacks. First, as a food consumption deprivation measure, it disregards overconsumption of calories. However, it also goes beyond dietary diversity scores in considering both whether a food group is consumed and the extent to which households are deprived within a food group. The measure also does not allow us to infer on nutritional status. Second, global reference diets, such as the EAT-*Lancet* diet, may not always be ideally suited to a particular country context, but in the absence of quantitative food-based dietary guidelines in many countries—including in Nigeria, our case study country—this is a useful approach. It also facilitates comparison of diet quality and costs across countries.

Third, there are some limitations to the use of household consumption and expenditure survey data for diet analysis. Most notably, they do not collect adequate information on food consumed away from home, while information on intra-household food allocation or food waste is often poorly captured. Of course, the ReDD index can equally be computed using individual food consumption data or food intake data (e.g., from 24-hour dietary recalls). Despite these limitations, the ReDD index has been shown here to be a rich measure of diet quality that can easily be computed from household survey data. It can be used either to track changes in diets over time (e.g., using panel data) or, when integrated into an economic model such as RIAPA, to simulate the impact of policies, investments, or external shocks on household diets.

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7 Appendix

Table A1. Detailed RIAPA commodity listing and mapping to ReDD food groups

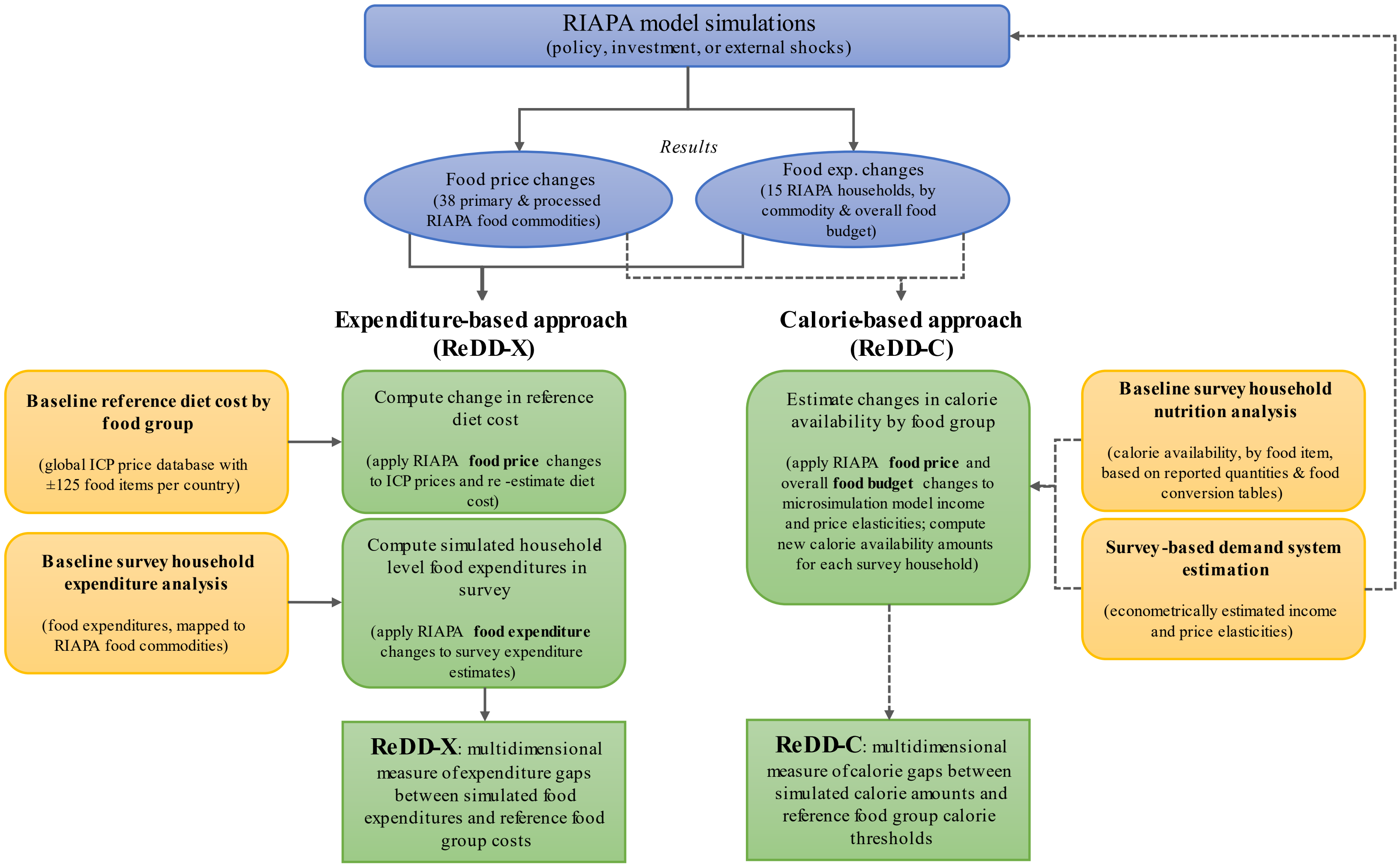
	RIAPA commodities			**ReDD food groups (costing)**		**ReDD food groups (index)**	
No.	**Desc.**	**Code**	**Sector**	**Desc.**	**Code**	**Desc.**	**Code**
1	Maize	cmaiz	Crops	Grain cereals	gcere	Starchy staples	gstap
2	Sorghum & millet	csorg	Crops				
3	Rice	crice	Crops				
4	Wheat and barley	cwhea	Crops				
5	Other cereals	cocer	Crops				
6	Maize milling	cmmll	Processing				
7	Sorghum and millet milling	csmll	Processing				
8	Rice milling	crmll	Processing				
9	Wheat and barley milling	cwmll	Processing				
10	Other grain milling	cgmll	Processing				
11	Other foods	cfood	Processing				
12	Cassava	ccass	Crops	Root crops	groot		
13	Irish potatoes	cipot	Crops				
14	Sweet potatoes	cspot	Crops				
15	Other roots	croot	Crops				
16	Plantains	cplan	Crops				
17	Leafy vegetables	cleaf	Crops	Vegetables	gvege	Vegetables	gvege
18	Other vegetables	cvege	Crops				
19	Fruit and vegetable processing	cfveg	Processing				
20	Bananas	cbana	Crops	Fruits	gfrui	Fruits	gfrui
21	Other fruits	cfrui	Crops				
22	Raw milk	cmilk	Livestock	Dairy foods	gdair	Dairy foods	gdair
23	Dairy	cdair	Processing				
24	Cattle	ccatt	Livestock	Animal protein	ganim	Protein sources	gprot
25	Poultry	cpoul	Livestock				
26	Eggs	ceggs	Livestock				
27	Small ruminants	csmlr	Livestock				
28	Other livestock	coliv	Livestock				
29	Aquaculture	caqua	Fisheries				
30	Capture fisheries	cfish	Fisheries				
31	Meat processing	cmeat	Processing				
32	Fish and seafood processing	cfsea	Processing				
33	Pulses	cpuls	Crops	Legumes & nuts	glegu		
34	Groundnuts	cgnut	Crops				
35	Other oilseeds	coils	Crops				
36	Nuts	cnuts	Crops				
37	Other crops	cocrp	Crops				
38	Fats and oils	cfoil	Processing	Added fats	gafat	Added fats	gafat

Table A1 continued…

Discretionary foods—not used in ReDD costing or index							
39	Sugarcane	csugr	Crops	Discretionary foods	gdisc	Discretionary foods	gdisc
40	Leaf tea	cteal	Crops				
41	Coffee	ccoff	Crops				
42	Cocoa	ccoco	Crops				
43	Sugar refining	csref	Processing				
44	Coffee processing	cpcof	Processing				
45	Tea processing	cptea	Processing				
46	Beverages	cbeve	Processing				

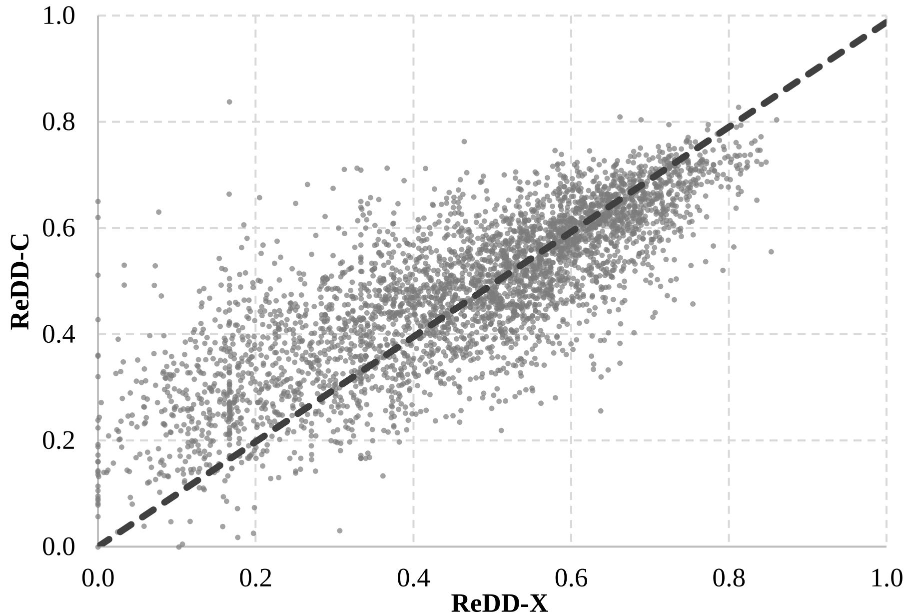
Source: Authors representation

Figure A1. Schematic representation of the approaches to modeling diet outcomes



Source: Authors' representation

Figure A2. ReDD-X and ReDD-C correlation



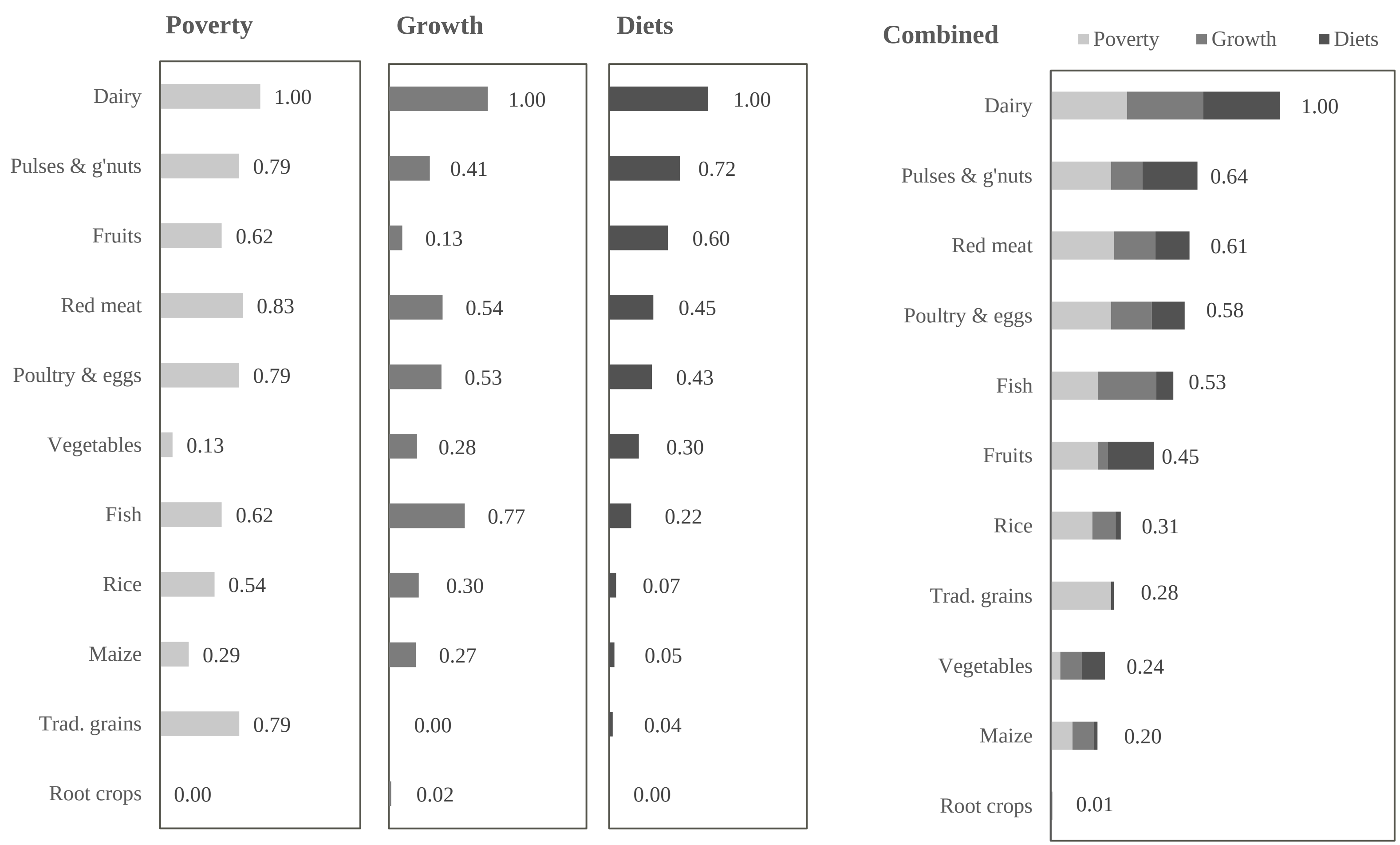
Source: Authors' estimates based on GHS-Panel 2015-16

Table A2. Nigeria income and own-price elasticities of food demand (2015/16)

	Expenditure elasticities		Own-price elasticities	
	Rural	***Urban***	***Rural***	***Urban***
Total food	0.739	0.673	-0.909	-0.819
Sorghum & millet	0.209	0.358	-1.006	-0.679
Rice	0.852	0.603	-0.633	-0.612
Maize & wheat	1.028	0.813	-1.486	-1.338
Cassava	0.271	0.103	-0.975	-0.531
Other starchy roots/tubers & plantains	0.626	0.726	-0.823	-0.885
Pulses & nuts	0.751	0.407	-0.921	-0.676
Vegetables	0.626	0.522	-0.655	-0.65
Fruits	0.855	0.997	-1.23	-1.078
Meat	1.344	1.156	-1.972	-1.585
Smoked & dried fish	0.311	0.820	-0.841	-0.817
Fresh & frozen fish	0.313	0.447	-0.435	-0.746
Dairy & eggs	0.906	0.937	-0.752	-0.591
Oils & fats	0.701	0.543	-0.527	-0.546
Sweeteners, condiments, snacks	0.447	0.502	-0.282	0.460
Beverages	0.961	0.892	-1.002	-0.993

Source: Ecker and Comstock (2021), based on GHS-Panel 2015-16.

Figure A3. Value chain ranking with multiple outcome indicators



Source: RIAPA model results.