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Measuring changes in diet deprivation: New indicators and methods

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A B S T R A C T

Improving diet quality is an emerging development policy priority. Existing indicators emphasize the cost and affordability of healthy diets but have not attempted to measure how far households are from ideal diets or how policies may nudge them closer to them. We propose a new Reference Diet Deprivation (ReDD) index, estimated from household consumption survey data, that measures the incidence, breadth, and depth of diet deprivation across multiple food groups. While informative as a standalone measure, we demonstrate how the ReDD index can be integrated into an economic model to examine changes in diet quality under different policy or external shocks. Our Nigerian case study shows that productivity growth in the dairy, pulse & nut, fruit, and red meat value chains have more potential than staple crops to reduce diet deprivation. While these findings have implications for food and agricultural policy prioritization in Nigeria, the study more importantly demonstrates the usefulness of the ReDD index for assessing diet quality and examining the drivers of dietary change when used in conjunction with a simulation model.

1. Introduction

Poor diet quality, as it relates to deficiencies, excesses, or imbalances in calorie and nutrient intakes, is universally recognized as a major cause of malnutrition and non-communicable disease (FAO et al., 2020; Hawkes et al., 2020), and is responsible for 22 percent of adult deaths globally (Afshin et al., 2019). The environmental sustainability of the global food system, which is increasingly associated with rising emissions and pollution, biodiversity loss, and unsustainable water and land use, has also come into question (GLOPAN, 2020; Godfray et al., 2010; Tilman et al., 2011). This served as motivation for the EAT-*Lancet* Commission on Food, Planet, Health to develop a universal, healthy reference diet that quantifies optimal food intakes by food group that would meet most people's nutritional requirements and reduce the incidence of nutrition-related disease and mortality (Willett et al., 2019). Further, if all people followed such a diet, the world would stay within the planetary boundaries for sustainable food production (Steffen et al., 2015).

Human diets are shaped by complex food systems and are highly context-specific, with cultural, geographical, or environmental factors driving consumer preferences. Therefore, although there are broadly accepted guidelines for what constitutes healthy eating – for example, diets should meet individual requirements for dietary energy and essential nutrients and avoid excess intake of unhealthy food components or certain nutrients beyond critical thresholds (Herforth et al., 2019; Tapsell et al., 2016) – there is no single, globally accepted definition of a healthy diet (Fanzo et al., 2022; Miller et al., 2020). For this reason, the healthy reference diet of the EAT-*Lancet* Commission (hereafter referred to as the EAT-*Lancet* diet), although broadly consistent with many national food-based dietary guidelines (see Herforth et al., 2022), is only be suggestive of what people should ideally consume (Willett et al., 2019).

A challenge for diet quality assessments – and by implication food policy design, implementation, and monitoring – has been the lack of consensus on the constructs of a healthy diet and appropriate metrics for measuring diet quality (WHO et al., 2021). While efforts to build such consensus are underway, it has meant that diet quality has been approximated by a variety of food or nutrient scoring measures. The most established of these are the Dietary Diversity Score (DDS) and the Food Variety Score (FVS), which are count measures of the number of food groups or items consumed (see Ruel, 2003). While count measures based on 24-hour food recall data have been validated against nutrient adequacy estimates in developing countries (see for example Becquey et al., 2010; Kennedy et al., 2007; Martin-Prevel et al., 2015; Steyn et al.,

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2006), they neither differentiate between the types of foods consumed nor do they measure consumption quantities against requirements.

The Diet Quality Index-International (Kim et al., 2003) overcomes some of the limitations of dietary diversity scores by adopting a complex scoring method that factors in food variety and nutrient adequacy aspects of diets. Although it has been proposed as a tool for cross-country comparisons, its usefulness in this regard has been questioned (Tur et al., 2005). Other food-based diet quality metrics include the Global Diet Quality Score (Bromage et al., 2021) and the Healthy Eating Index (Krebs-Smith et al., 2018). These require detailed food frequency questionnaires for data collection. Another drawback of food-based diet quality metrics is that they typically do not specify (universal) cutoffs for defining diet quality (Miller et al., 2020). An exception is the Minimum Dietary Diversity for Women (MDD-W), which sets a lower-bound threshold for dietary diversity of women of reproductive age (FAO, 2021). This permits a ranking of outcomes relative to a threshold, but this measure has been shown to perform poorly when compared with nutrient adequacy-based indicators (see Nguyen et al., 2018). In summary, while existing score-based diet quality measures have useful features, they also have many shortcomings which limit their applicability in dietary assessments.

Since the EAT-*Lancet* diet defines reference consumption quantities representing an aspirational or ideal diet, it can in principle serve as a basis for assessing the quality of individual diets. Understandably, any attempt to define ideal intake levels at a global level will attract criticism. For example, the scientific basis for the claim that the EAT-*Lancet* diet can prevent malnutrition and non-communicable disease in every context has been questioned (Blackstone and Conrad, 2020; Leroy and Cofnas, 2020; Zagmutt et al., 2020). Of course, the EAT-*Lancet* diet intakes should not be interpreted as absolute thresholds that must be achieved; rather, they serve as benchmarks for an ideal diet that provides enough calories and is nutritionally balanced. And despite attracting critique, the EAT-*Lancet* diet has spurred interest among development and food policy analysts in topics such as the cost and affordability of healthy diets (e.g., Hirvonen et al., 2020; Headey et al., 2023) and has motivated others to explore alternative constructs of international reference diets (e.g., Bai et al., 2022; FAO et al., 2020; Laborde et al., 2021). The EAT-*Lancet* diet has also been used as basis for constructing new score-based diet quality indexes from food frequency data (e.g., Cacau et al., 2021; Knuppel et al., 2019; Stubbendorff et al., 2022). We too select the EAT-*Lancet* diet as default reference diet underlying the diet quality metric proposed in this paper, although as our metric can equally be computed using other suitable national or international quantitative reference diets, where available.

Beyond an interest in measuring diet quality or assessing the affordability of healthy diets, policymakers may also wish to understand the drivers of dietary change, and how these are influenced by policies. Consumers' food preferences, as manifested in behavioral responses to changes in relative food prices or incomes, are important determinants of consumption choices and hence diet quality (McCullough et al., 2022; Clements and Si, 2017). However, this behavior is not independent of the broader food system; instead, it is linked to food environments, that is, the places and contexts in which consumers access food, as shaped by personal circumstances, norms, markets, and policies (Herforth and Ahmed, 2015; Swinburn et al., 2015; Turner et al., 2018). 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 are further influenced by demographic, socio-cultural, political, economic, technological, and environmental drivers (Fanzo et al., 2020; GLOPAN, 2016; Swinburn et al., 2013). It is evident that 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 (Brouwer et al., 2020; Fan et al., 2021; Foran et al., 2014).

With this context in mind, we have two objectives in this paper. The first is to introduce a new diet quality measure called the Reference Diet Deprivation (ReDD) index. The ReDD methodology is inspired by the Multidimensional Poverty Index (MPI) (Alkire and Foster, 2011). Specifically, we adopt the adjusted deprivation gap measure in the family of MPI indicators as our ReDD index. Whereas the MPI usually measures deprivation in non-monetary dimensions of wellbeing, such as education or health, the ReDD index measures what we term "diet deprivation" within and across several distinct food groups. Diet deprivation here is defined as the voluntary or involuntary shortfall in consumption relative to a chosen consumption threshold. The ReDD index is computed using household consumption and expenditure survey data and involves a comparison of household food consumption across a distinct number of food groups against reference consumption thresholds defined by a chosen reference diet, such as the EAT-*Lancet* diet. The ReDD index itself is a composite of indicators measuring the incidence, breadth, and depth of diet deprivation. It can be based either on households' reported expenditures or their calorie consumption amounts by food group. In the case of the latter, the reference consumption quantities are expressed in calories, while in the case of the former, a cost estimate of the reference diet that correlates with the calorie thresholds is used. In this paper we showcase both expenditure-based (ReDD-X) and calorie-based (ReDD-C) versions of the index.

Although the ReDD index can be used as a standalone measure to compare diet quality across households or populations or track changes in diet quality over time, a second objective of this paper is demonstrating the usefulness of the ReDD index for conducting policy impact assessments in combination with other methods. Specifically, we showcase how the ReDD index can be integrated into an economywide modeling framework to examine changes in household diet quality under different policy scenarios or external shocks. The Rural Investment and Policy Analysis (RIAPA) model is an economywide framework that captures the interactions of producers and consumers in an economy (see Diao and Thurlow, 2012). A unique feature of RIAPA is its detailed representation of the agrifood system, making it ideally suited for examining implications of policies, investments, or shocks on food supply, household food budgets, and relative food prices, which in turn drive food consumption choices. 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 using alternative specifications of survey-based microsimulation models linked sequentially to the RIAPA model.

The remainder of the paper is structured as follows. Section 2 introduces key concepts relating to reference diets, diet costing, and the mathematical derivation of ReDD. We also present baseline estimates of the ReDD-X and ReDD-C indexes for Nigeria. Section 3 introduces the RIAPA model and microsimulation modules, while Section 4 presents the simulation setup and results. Section 5 draws conclusions and highlights limitations and advantages of the ReDD index.

2. The reference diet deprivation (ReDD) index

2.1. Overview

The ReDD index is a population-level multidimensional indicator of household diet deprivation. It is multidimensional because it considers consumption shortfalls across multiple food groups. The ReDD index is estimated from household food consumption data. A household is considered deprived in a food group if its observed consumption is less than the reference consumption quantity for that food group, as defined by a reference diet, irrespective of whether underconsumption is voluntary or involuntary. The ReDD index combines information on consumption shortfalls across all food groups and all households. The resulting measure can also be decomposed into three components, namely 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 people are deprived (breadth of deprivation); and the relative average gap between observed consumption and reference consumption quantities (depth of deprivation).

While the choice of reference diet is a subjective one – the ReDD index can, in principle, be based on any quantitative reference diet, including national food-based dietary guidelines, that specify recommended or optimal food quantities or calorie intakes across multiple food groups – our default choice is the EAT-*Lancet* diet (Willett et al., 2019). This is partly because Nigeria, our case study country, does not have its own national food-based dietary guidelines. The EAT-*Lancet* diet is also globally recognized and serves as an objectively defined optimal or ideal diet that facilitates diet quality comparisons across countries. We further assess diet quality across six food groups, namely starchy staples (including cereals and root crops); vegetables; fruits; dairy foods; protein foods from both animal sources (meat, fish, and eggs) and plant sources (pulses and nuts); and added fats. These are constructed directly from the major food groups in the EAT-*Lancet* diet, although the ReDD methodology is flexible to accommodate other food groupings, e.g., those defined by national food-based dietary guidelines.

The ReDD index is computed using household consumption and expenditure survey data. These surveys measure food consumption in expenditure and/or quantity terms (e.g., grams) for large numbers of commonly consumed foods. While consumption is typically reported for the household, it is standard practice to convert estimates into per adult equivalents per day. Reference food consumption quantities from the reference diet are also typically specified in quantity terms and/or dietary energy (i.e., calories) per adult equivalent per day. Depending on preferences or how the survey data is constructed, consumption shortfalls for the ReDD index can be measured in two ways. Under an expenditure-based version (ReDD-X), household food expenditure on a food group is compared against the reference cost of that food group. The reference costs correspond to the optimal food intakes in the reference diet. Alternatively, under a calorie-based version (ReDD-C) the household's calorie consumption from each food group is compared against the optimal calorie intake for that food group. If the reference diet specifies optimal food intake in quantitative terms, these should be converted to calories using calorie conversion factors.

The ReDD index has several useful features. First, the ReDD index goes beyond score-based indicators, such as those introduced earlier, by not only counting the number of food items or groups consumed, but also measuring food consumption shortfalls in relation to a reference diet. This allows an assessment of the depth of diet deprivation within and across food groups. Second, and relatedly, the ReDD index conveys information about diet quality, as represented by the distance between observed diets and an ideal reference diet. This means household or population diets can be unambiguously ranked in terms of their quality. Similarly, the ReDD index can be used to track changes in diet quality over time or assess the impact of policies on diet quality using ex post evaluation or ex ante simulation methods. These features signify a distinct advantage of the ReDD index over existing score-based diet quality measures, which as discussed are limited in their applicability in dietary assessments.

Third, the ReDD index is computed using commonly available household consumption and expenditure survey data. As with poverty estimates, the ReDD index can be estimated relatively easily, and as often as new household surveys are conducted. Although the ReDD index itself is a population-level measure, it is constructed from household-level data on consumption shortfalls, and therefore decomposable by population subgroup. This permits more nuanced assessments of diet deprivation that are sensitive to the fact that even though national food supplies might be adequate, there may still be inequality in the access and utilization of food across households (Barrett, 2010). By the same token, of course, food consumption data from household surveys do not typically provide information on the intrahousehold allocation of food, which necessitates an assumption that food is allocated in proportion to the dietary requirements of individual household members.

2.2. Choosing a reference diet

The first step in constructing the ReDD index is choosing an appropriate reference diet. The reference diet identifies the food groups and reference consumption quantities against which consumption shortfalls are assessed. In principle, any quantitative reference diet that specifies optimal or ideal food consumption or calorie intakes in quantitative terms (i.e., grams or calories) across multiple food groups can be used. As argued, the EAT-*Lancet* diet (Willett et al., 2019) is suited for this purpose, and so too are some of its variants, such as the flexitarian, pescatarian, or vegetarian diets (Springmann et al., 2021).

National food-based dietary guidelines may also be used, provided they specify reference consumption intakes in quantitative terms. These guidelines may be deemed more appropriate than global reference diets as they consider the cultural, geographical, and environmental factors that drive consumer preferences. Admittedly, many countries' food-based dietary guidelines do not offer the type of specificity required to estimate the ReDD index, although more and more countries are developing guidelines that would be suitable. One possible solution to this is offered by Herforth et al. (2022), who construct their so-called healthy diet basket from several countries' national food-based dietary guidelines. Th healthy diet basket can also be used as a reference diet for the ReDD index.

We opt for the EAT-*Lancet* diet as reference diet for analysis in this paper. Table 1 reports reference food quantity and calorie intakes of the EAT-*Lancet* diet by food group, specified for a moderately active average adult (Willett et al., 2019). The EAT-*Lancet* diet includes eight major food groups. For the ReDD index we combine two of these—cereal grains and root crops—into a staple food group. A similar aggregation was made by Springmann et al. (2021) as this allows substitution between these staple foods, thus accounting for geographical differences in the main sources of calories. Added sugars are a distinct major food group in the EAT-*Lancet* diet, but we drop this food group from the ReDD index since these foods have no nutritional value and are regarded as non-essential (Willett et al., 2019). By focusing on six essential food groups, the ReDD methodology can accommodate most people's dietary patterns and food preferences. This includes relatively common diets such as flexitarian, pescatarian, or vegetarian diets, but not vegan diets, which exclude dairy products. Of course, vegan diets are unlikely to be nutritionally adequate without nutrient supplements and are therefore not commonly followed or recommended in developing countries.

Three features of the EAT-*Lancet* diet are worth highlighting. First, by setting ranges of intakes, Willett 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, intake ranges for some food items start at zero, signifying that not all food items must necessarily be consumed to still achieve a healthy diet. Consuming more than the upper bound is acceptable for some foods such as vegetables—albeit digestively difficult to sustain over a longer time—but upper bounds for others are considered thresholds that should not be exceeded. For example, calories from cereal grains should account for no more than 60 percent of total daily caloric intake, while added sugars should not exceed five percent of dietary energy.

Second, Willett et al. (2019) also specify optimal calorie intakes for each food group. These amounts are derived roughly from the midpoints of the range of food quantities. When summed together, these midpoints provide 2,500 kcal per day for a representative moderately active adult. This is comparable with the recommended intakes of moderately active female (2,350 kcal) and male (2,850 kcal) adults (FAO et al., 2001). While the calorie intakes should not be interpreted as absolute thresholds that must be achieved, they provide useful benchmarks for an

Table 1
Reference intakes and cost of the EAT-*Lancet* diet *Source:* Reference intakes are taken from Willett et al. (2019) and food prices are derived from World Bank (2020).

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

Note: kcal = kilocalories; ICP = International Comparison Program (World Bank, 2020); PPP = purchasing power parity; NGN = Nigerian Naira.

aspirational or ideal diet that yields enough daily calories obtained from a diverse set of nutritious food groups.

Third, the first six food groups as numbered in Table 1 are considered nutritionally required—or essential—food groups, which means consumers should ideally consume foods from all these groups for their diets to be considered balanced and healthy. Although calories from added sugars are permitted, the food group is considered non-essential, and calories from added sugars can be replaced with those from other food groups. Consumption of unhealthy foods such as sweets, salty snacks, sugary beverages, and fast foods are discouraged (Willett et al., 2019). The ReDD index excludes these non-essential and unhealthy foods, i.e., the index is computed solely based on deprivation in the six essential food groups. However, we do include calories derived from non-essential and unhealthy foods in the measurements of total food expenditure or total calorie consumption.

2.3. Costing the reference diet

The calorie-based version (ReDD-C) requires estimates of household calorie consumption by food group, which are obtained by applying calorie conversion factors to reported food consumption quantities. Calorie consumption amounts are then compared against reference calorie intakes to estimate the ReDD index. Conversely, under the expenditure-based version (ReDD-X), household food expenditure, which is typically reported in the survey data, is compared against the reference cost of the food group. The diet costs should correspond to the calorie intakes of the reference diet.

A large body of literature has developed around costing (and affordability) of healthy diets (Bai et al., 2021, 2022; Headey and Alderman, 2019; Hirvonen et al., 2020). Whereas diet costing exercises have generally focused on the overall cost of diets, the ReDD-X index compares food expenditures in each food group against a reference cost for that food group. Our costing approach follows Hirvonen et al. (2020) in that we identify a reference food item for each food group and multiply 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). The cheapest item in each food group, measured in per calorie terms, is selected as reference item.

Table 1 demonstrates the costing method using prices in Nigerian Naira (NGN) from the ICP database (2017 prices). Within the staples group, costs are first estimated separately for the cereal and root crop subgroups before they are aggregated. The same applies to protein foods, where costs of animal- and plant-based proteins are estimated separately before they are aggregated to the food group level. This means for both these groups two reference prices enter the costing equation for the main food group. The remaining food group costs are all derived from a single reference item. Consider the example of fruits. Within this group, short finger bananas are the cheapest item (NGN 0.338 per kilocalorie), which when multiplied by the reference calorie intake (126 kcal) yields a daily cost of NGN 42.61 per adult equivalent per day.

Since the price of the cheapest item is used as reference price, the food group cost represents the lowest possible cost at which the reference calorie amount can be acquired. Someone who spends less than NGN 42.61 on fruits will, by default, not obtain enough calories from that group; conversely, someone who chooses to consume more expensive mangoes would not achieve enough calories if they spent NGN 42.61, even though this method would deem that person capable of consuming enough calories. This highlights an important definitional distinction between the ReDD-X and ReDD-C versions, where the latter is based on an assessment of actual calorie consumption rather than food expenditures. The distinction between the two index values is discussed further in section 2.5.

The EAT-*Lancet* diet has attracted critique for being unaffordable to many of the world's poor. For example, Hirvonen et al. (2020) find that the cost of the EAT-*Lancet* diet exceeds total per capita expenditure of 62 percent of people in low-income countries. The fact that our own diet cost estimate for Nigeria (USD 3.19) is well above the World Bank's international poverty line (USD 2.15) underscores this fact. Of course, the calorie intakes in reference diets should not be confused with minimum calorie thresholds that underlie poverty analyses. In Nigeria, for example, the poverty line is based on the cost of acquiring 2,251 kcal from a food basket dominated by low-cost, calorie-dense foods (World Bank, 2022). Instead, the EAT-*Lancet* diet should be viewed as an ideal diet, and while reducing the share of the population that cannot afford the diet is a noble policy target, our analysis is motivated more by the imperative to reduce relative consumption gaps across all food groups, i.e., to bring people closer to that ideal diet. This is in line with the idea that addressing food system failures should not only be about producing enough calories, but rather about closing diet quality or nutrient gaps for everyone (Béné et al., 2019).

2.4. Deriving the ReDD index

The method for computing the ReDD index is inspired by the Multidimensional Poverty Index (MPI) developed by Alkire and Foster (2011). The MPI is most often used to study deprivation in non-monetary dimensions of wellbeing, such as education or health. It 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 within that dimension. At the second stage, if an individual is deprived in more than a certain number of dimensions—that number is a subjective choice—the person is considered multidimensionally deprived.

The six essential food groups underlying our diet analysis are used as the dimensions in which diet deprivation is measured. Since the deprivation assessment is based on household consumption and expenditure survey data, the unit of observation is the household. If a household is deprived, every member of that household is considered deprived, an unavoidable assumption in the absence of information on the intra-household allocation of food. As noted, in the case of ReDD-X, household food group expenditure is compared against the reference cost of that food group to identify households that are deprived, while in the case of ReDD-C, calorie consumption is compared against the optimal caloric intakes in the reference diet. Optimal calorie intakes and food group cost estimates as well as food expenditures and calorie consumption amounts should be expressed in comparable units, i.e., currency units or kilocalories per adult equivalent per day. Converting to adult equivalents entails dividing household-level estimates by a household size measure that is adjusted for the gender and age composition of the household. This accounts for the fact that not all household members have the same dietary energy requirements as a reference adult (FAO et al., 2001).

Formally, we define x_{ij} as the expenditure, or calorie consumption, in per adult equivalent terms, of household $i = 1, \cdots, n$ for food group $j = 1, \cdots, d$, while z_j denotes the cost, or caloric intake, threshold for food group j. A matrix of normalized gaps g^{α} can now be defined for $\alpha = 0, 1 \text{ or } 2$, where α is analogous to the parameter in the Foster-Greer-Thorbecke (FGT) class of poverty measures (Foster et al., 1984):

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

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 takes on the value of one if the household is deprived in food group j and zero otherwise:

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

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 food group deprivations in the measurement of overall diet deprivation. For example, sufficient consumption of starchy staples, an important source of inexpensive calories, may be considered vital in a context where hunger is widespread; or, sufficient consumption of dairy and protein foods, both of which are important sources of micronutrients, may be considered critical in a context of widespread micronutrient malnutrition. If such motivations exist, greater weights may be attached to these dimensions or food groups. Since we deem all essential food groups as equally important, equal weights are used as default, i.e., $w_j = 1/d$ for all values of j.

Summing over the weighted deprivations yields a deprivation score $c_i^0 = \sum_{j=1}^{d} w_j . g_{ij}^0$. For the second-stage identification we define the multidimensionally deprived as those suffering $k \in [1, \cdots, d]$ 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, and vice versa. We set $k = 1$ as the default, meaning anyone who is deprived in one or more of the food groups is considered diet deprived. This 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:

$$\rho_k = \begin{cases} 1 \text{ if } c_i^0 \geq \dfrac{k}{d} \\ 0 \text{ if } c_i^0 < \dfrac{k}{d} \end{cases} \tag{3}$$

The ReDD index is a composite of three separate indicators, each with a unique interpretation. The first indicator is the headcount rate, H, which is the share of population that is multidimensionally deprived ($\rho_k = 1$). Given the high reference calorie intakes and costs of food groups in the EAT-*Lancet* diet, as well as the low dimensional cutoff ($k = 1$), we expect the value of H to be high, since even wealthy households in Nigeria will tend to under-consume calories from at least one food group. We revisit the implications of this later. 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:

$$H = \frac{1}{n}\sum_{i=1}^{n} \rho_k = \frac{q}{n} \tag{4}$$

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:

$$A = \frac{1}{q}\sum_{i=1}^{q} c_i^0(k) = \frac{1}{q}\sum_{i=1}^{q}\sum_{j=1}^{d} w_j . g_{ij}^0(k) = \frac{1}{q}\sum_{i=1}^{q}\sum_{j=1}^{d} w_j . g_{ij}^0 . \rho_k \tag{5}$$

Alkire and Foster (2011) define their adjusted headcount ratio, M_0, as the product of H and A. While this measure is sensitive to the incidence and breadth of deprivation, it is not sensitive to the depth of deprivation, which is important given our interest in also measuring how far people are, on average, from consuming an ideal or optimal diet. Moreover, given our high value of H, M_0 would converge to A, which has the same limitations as count-based dietary diversity indicators. We therefore opt to use the adjusted deprivation gap measure, M_1, as our ReDD index. For $\alpha = 1$ the normalized gap matrix g^1 takes on the following values:

$$g_{ij}^{1} = \begin{cases} \left(z_j - x_{ij}\right)/z_j \text{ if } x_{ij} < z_j \\ 0 \text{ if } x_{ij} \geq z_j \end{cases} \tag{6}$$

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 ReDD index can then be expressed as follows:

$$ReDD = M_1 = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{d} w_j.g_{ij}^1(k) = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{d} w_j.g_{ij}^1.\rho_k = H.A.G \quad (7)$$

As shown, the ReDD index is the product of H, A, and G. G measures the average deprivation gap across all food groups, and is derived from the following equation:

$$G = ReDD/H.A \quad (8)$$

Alkire and Foster (2011) also propose a third measure of multidimensional deprivation, M_2, which is derived from squared censored normalized gap matrix, $g_{ij}^2(k)$. Squared consumption gap measures attach greater weight to people with larger deprivation gaps. However, poverty measures that factor in inequality among the deprived lack intuitive appeal (Deaton, 1997) and are not widely used in applied policy analysis. For this reason, we prefer M_1 over M_2 as our ReDD index.

2.5. Two alternative specifications of the ReDD index

Although the ReDD-X and ReDD-C versions can often be computed with the same survey data and are methodologically consistent, they measure somewhat different aspects of diet deprivation. Under the ReDD-X version, households who spend at or above the food group cost would be considered not deprived in that food group, even though some of these households might not meet calorie requirements because they choose more expensive foods than the least-priced item used in the diet cost calculation. In the cost-of-basic-needs poverty literature the classification of non-deprived in this instance is justified because the household is deemed to have the *capability* to meet basic needs (Arndt et al., 2017). The ReDD-C version, on the other hand, is based on reported calorie consumption, which brings the approach more in line with the use of context-specific poverty lines based on revealed preferences of households across all contexts, locations, or seasons.

Despite these distinctions, population-level diet deprivation estimates are found to be comparable across the expenditure- and calorie-based approaches, at least in our Nigerian case study. Results in Table 2 are based on the subset of 3,778 households that were interviewed in both the post-planting and post-harvest seasons of the panel component of the 2015–2016 Nigeria General Household Survey (NBS and World Bank, 2016, 2018) (we refer to the dataset as the Nigeria GHS Panel 2015-2016 in the remainder of the paper). Food expenditures and consumption quantities are based on a seven-day recall of 116 food items, while West African food conversion tables (Stadlmayr et al., 2012) are used to convert food quantities into calorie amounts. For a more detailed discussion of the treatment of the data, see Ecker and Hatzenbuehler (2022).

As shown in Table 2 both the expenditure- and calorie-based approaches yield similar incidences of deprivation by food group, i.e., the percentages of people with expenditures or calorie consumption below the reference consumption levels. The largest difference between the two approaches is in protein foods (79.7 versus 94.3 percent), which reflects a preference for more expensive meat or fish over beans as a source of protein in Nigeria. The second column shows the average food expenditure or calorie consumption gaps at national level. The lower calorie consumption gaps for fruits (58.1 versus 73.8 percent) and dairy (76.2 versus 88.1 percent) may reflect that households access these foods – and hence the calories derived from that consumption – at lower prices than those obtained from the ICP price database. The third column shows the contribution of food groups to the national ReDD index estimate. Food group contributions are similar across the two approaches, except for a higher contribution from protein foods (20.2 versus 17.9 percent) and lower contributions from fruits (19.4 versus 20.3 percent) and dairy (20.8 versus 22.1 percent) foods, which is consistent with the differences in incidences of deprivation and consumption gaps highlighted above.

The bottom half part of Table 2 reports values for the ReDD-X and ReDD-C indexes as well as their components, H, A, and G. The headcount ratio of deprived people (H) is close to one under both specifications, meaning that almost no Nigerian household in our sample has food expenditure or calorie consumption amounts that meet EAT-*Lancet* diet thresholds across all food groups simultaneously. As argued earlier, this is expected given our choice of dimensional cutoff ($k = 1$) and the fact that the EAT-*Lancet* diet should be regarded as an aspirational, ideal diet. Given the extent of the consumption gaps in all but the staple food group, it is unlikely that any policy will raise incomes or reduce food prices by enough to cause meaningful shifts in H. The headcount rate is therefore not a meaningful policy variable to target; instead, the interest of policymakers should be directed to the average deprivation share (A) and the average food consumption gap (G), both of which are gap measures that indicate proximity to an ideal diet rather than attainment of that diet.

To further put the high headcount ratio in perspective, the last row in Table 2 reports that 22.4 percent of households defined as diet deprived in terms of the expenditure-based approach have total food budgets that exceed the total cost of the EAT-*Lancet* diet. The implication is that these households could theoretically afford the reference diet if they reallocated their food expenditures. Likewise, 56.6 percent of households defined as diet deprived in terms of the calorie-based approach consume

Table 2

Diet deprivation estimates for Nigeria: Expenditure- and calorie-based approaches *Source:* Authors' estimates based on Nigeria GHS Panel 2015-2016.

	Expenditure-based (ReDD-X)			Calorie-based (ReDD-C)		
	Incidence of deprivation (%)	Avg. food cons. gap (%)	Contribution to ReDD (%)	Incidence of deprivation (%)	Avg. food cons. gap (%)	Contribution to ReDD (%)
Food group indicators						
Starchy staples	11.6	2.6	2.6	13.2	2.3	2.8
Vegetables	91.1	56.1	20.4	95.9	54.1	20.6
Fruits	90.6	73.8	20.3	90.6	58.1	19.4
Dairy foods	98.6	88.1	22.1	97.1	76.2	20.8
Protein foods	79.7	43.0	17.9	94.3	49.2	20.2
Added fats	74.3	32.7	16.7	75.4	27.8	16.2
	National	Urban	Rural	National	Urban	Rural
ReDD index components						
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 ($H.A.G$)	0.494	0.432	0.528	0.517	0.494	0.528
Share (%) of diet deprived (1) able to afford reference diet OR (2) with calorie consumption above overall reference diet requirement	22.4	30.1	18.1	56.6	46.5	61.7

more than 2,500 kcal per adult equivalent in total and are therefore not food insecure, although they do have nutritionally unbalanced diets. In short, the percentage of diet deprived households that can afford the EAT-*Lancet* diet is relatively low because the reference diet is expensive and does not represent what people choose to consume; likewise, the percentage of diet deprived people who access enough calories in total is relatively high because most people access the bulk of their calories from inexpensive and calorie-dense staples.

The average deprivation shares (A) for the ReDD-X and ReDD-C versions are 0.747 and 0.778, respectively, which means the average household suffers deprivation in four to five food groups out of a possible six. The average food consumption gap (G) under both index specifications is about two-thirds. The overall ReDD-C index estimate (0.517) is approximately five percent higher than the ReDD-X index estimate (0.494), with the difference explained entirely by the difference between the index values in urban areas.

Fig. 1 is a scatterplot of household-level estimates of ReDD-X and ReDD-C, obtained from the equation $ReDD_i = \sum_{j=1}^{d} w_j \cdot g_{ij}^{1} \cdot \rho_k$ (compare Equation (7)). The coordinates displayed in the figure are the population means for ReDD-X and ReDD-C (compare Table 2). The Pearson correlation coefficient ($\rho = 0.798$) reveals a strong and positive correlation between ReDD-X and ReDD-C, which implies that the approach of selecting the cheapest food item as reference item when costing the reference diet yields a reasonable estimate of the number of calories consumed. Put differently, the revealed preference of households is reasonably consistent with least cost diets.

Although a detailed discussion is omitted, we also estimate Pearson correlation coefficients between ReDD-X and ReDD-C and a Dietary Diversity Score (DDS) as well as a Food Variety Score (FVS). These scores are from Ecker and Hatzenbuehler (2022) estimated from the same household survey sample. As expected, ReDD-X and ReDD-C are negatively associated with the DDS (-0.515 and −0.436) and the FVS (-0.533 and −0.467). The moderate strength of the association can be explained by the fact that both sets of indicators capture aspects of dietary diversity. However, the ReDD index goes beyond dietary diversity by also incorporating a measurement of the depth of diet deprivation.

In summary, although the two versions of the ReDD index measure different aspects of diet deprivation, they are highly correlated. We also cannot definitively promote one version over another. Food expenditure data used in the ReDD-X version are widely accessible and arguably less prone to measurement error than the food quantities and derived calorie consumption amounts required for the ReDD-C version. The ReDD-X index, however, requires diet cost estimates, which could also introduce bias depending on the reliability of price data. Our default approach to diet costing relies on ICP prices. These do not reflect seasonal and regional retail price differences in local markets, which may also introduce a bias, even though we apply temporal and spatial deflators to food expenditure estimates in the survey. Ultimately, the choice between ReDD-X and ReDD-C boils down to a question of data availability and quality, as well as between deprivation analyses that respectively emphasizes households' capability to meet basic needs versus their revealed consumption preferences.

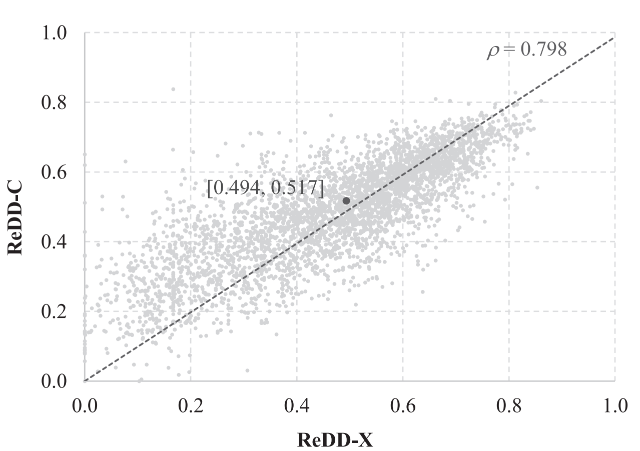

Fig. 1. Correlation between ReDD-X and ReDD-C household estimates and population means of the two index specifications. *Source*: Authors' estimates based on the Nigeria GHS Panel 2015-2016.

3. Modeling dietary change

3.1. Economwyide 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 the IFPRI recursive-dynamic computable general equilibrium (CGE) model that captures the linkages and market interactions between producers and consumers in an economy (Diao and Thurlow, 2012). The CGE model incorporates common behavioral features, including multi-level nested production functions, imperfect substitution between domestic and imported commodities, and a linear expenditure system of consumer demand. 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. Total public and private savings determine the level of investment under a savings-driven investment closure. The external balance is maintained through a flexible exchange rate.

Several unique features make the RIAPA model an ideal policy analysis and decision-making tool that is especially suited to analyzing food consumption choices. 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—including those designed to estimate changes in ReDD-X and ReDD-C described in the next section—the RIAPA model 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 a range of economic and socio-economic outcomes, and the diverse set of outputs and indicators produced by the RIAPA model can inform those decisions.

For the analysis presented here the RIAPA model is calibrated to a 2018 SAM for Nigeria (Thurlow, 2021). The SAM 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. The latter includes both primary agricultural commodities from the crops (23), livestock (6), and fisheries (2) subsectors and processed food commodities from the manufacturing sector (15). Model simulations generate results on consumption choices and real food price changes for the 15 households and 46 food items, which in turn have implications for diet costs and diet deprivation that are assessed in the microsimulation models linked to the RIAPA model. Table A1 in the appendix provides a complete list of food commodities in the model and their mapping to the reference diet food groups. Note that among the 46 RIAPA food commodities, 8 are mapped to discretionary foods, which contribute to total diet cost and calories, but are not considered in the

ReDD index.

3.2. Microsimulation modules

The recursive-dynamic setup of the RIAPA model allows us to track changes in economic variables over time under various simulation scenarios. At each timestep, simulated outcomes are compared against a business-as-usual baseline scenario. Changes in disposable incomes and food prices are important determinants of dietary change. To evaluate diet outcomes, household groups in the RIAPA model are mapped to individual households in the Nigeria GHS Panel 2015-2016 and the implications of modeled changes in food expenditures and prices relative to the baseline are assessed for individual households using a microsimulation model.

Two algorithms have been developed to accommodate the computation of the ReDD-X and ReDD-C indexes, respectively. For the estimation of the ReDD-X index, we rely on a top-down macro–micro model where simulated percentage changes in food group expenditures by representative households in the RIAPA model are applied to food expenditure estimates of individual households in the survey. We similarly utilize simulated food price changes from the RIAPA model to estimate a new cost of the reference diet. The revised food expenditure and diet cost estimates are used to compute new values for ReDD-X for each simulation, which are compared to baseline ReDD-X index values to assess changes in diet quality.

The ReDD-C algorithm similarly links to the RIAPA model in a top-down fashion. However, rather than applying percentage changes in food group expenditures, we link simulated changes in total food budgets of representative households in the RIAPA model to food budgets of individual households in the survey. Price changes are also linked to the microsimulation model, but since the reference consumption amounts are expressed in constant calories, there is no need to revise the cost of the reference diet. Instead, changes in food budgets and food prices are imported into a demand system calibrated with econometrically estimated income and own-price elasticities of demand, which is used to compute post-simulation calorie consumption amounts for each household. These are compared against calorie intakes in the reference diet to compute new values of ReDD-C.

The Online Supplementary Material provides a more detailed technical description of the expenditure- and calorie-based microsimulation approaches. It also includes the income and own-price elasticities of demand for Nigerian households used in the calorie-based microsimulation model, as well as a graphical representation of the two approaches. It should be noted that the ReDD-C index can also be estimated using the non-behavioral version of the microsimulation model, with some modification. Likewise, the ReDD-X index can be estimated using the behavioral version of the microsimulation. The behavioral microsimulation model arguably offers a more nuanced assessment of food consumption changes at the individual household level, but it requires a fully estimated demand system. Estimating such a demand system may not always be feasible given resource constraints or data limitations.

4. Simulation 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. Although designed primarily for demonstration purposes, the scenarios highlight the potential of productivity-enhancing, sector-specific agricultural investments in changing food environments and diets via 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. Value chain scenarios were conducted for over 20 value chains or value chain groupings representing the full spectrum of agricultural value chains in Nigeria. We present results for six of those value chain scenarios in this paper: (1) rice, (2) vegetables, (3) fruits, (4) pulses and nuts, (5) red meat (beef, goat, and sheep), and (6) dairy.

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 3). In each value chain scenario, 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 (or an additional 0.017 percentage points) in each value scenario.

Since this is a comparative analysis across value chains, the relative size of the shock is immaterial. The objective is not to identify sources of growth or assess the growth potential, but to compare the effectiveness of GDP growth originating in targeted value chains on household diets. By normalizing the marginal GDP effect across scenarios, the size effect of larger agricultural subsectors is neutralized, and the scenarios are broadly comparable in the sense that they generate similar increases in national household income. The objective is also not to conduct a detailed costing of policies, technologies or investments required to achieve productivity gains or to internalize those costs in the model. Such an exercise, while possible using the RIAPA model (see for example Aragie at al., 2022), is beyond the scope of this paper.

Of course, normalization does mean smaller value chains need to grow faster than larger ones to achieve the same increase in overall GDP. As shown in Table 3, the small dairy sector makes up only 0.33 percent of total GDP, and so TFP growth needs to be raised by 3.27 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 vegetable sector required to generate the same amount of additional GDP is only 0.31 percentage points above baseline. Since this assumption does potentially bias outcomes in favor of small sectors with large, simulated productivity gains, we also provide an alternative set of results in the appendix (see Table A2 in Appendix) where a uniform one percentage point gain over baseline factor productivity is imposed across all value chains. We refer to these alternative simulation results throughout the discussion.

4.2. Macroeconomic results

Table 3 also reports average GDP growth rates during 2020–2025 in the baseline as well as deviations from baseline growth in the value chain scenarios. As noted, 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 or red meat) have a noticeable impact on growth in the industrial or services sectors. Within the agricultural sector, the incidence of growth falls mostly on either the crops or livestock subsectors depending on the sector classification of the associated value chain (see highlighted cells).

Competition for resources is an important feature of the RIAPA model. When productivity is raised in a particular value chain, it lowers production costs and prices. This raises demand for output from that value chain, thus creating incentives to increase output further. The resulting competition for land and labor inputs affects other value chains that compete for the same resources. For example, as seen in Table 3, when productivity is raised in crops value chains, livestock GDP generally declines, and vice versa. Competition for resources also explains the small but economically significant differences in

Table 3
Simulation setup and simulated GDP impacts, 2020–2025 *Source: RIAPA model results.*

	Baseline scenario (%)	Value chain scenarios: Deviation from baseline GDP growth during 2020–2025 (%-point)					
		Rice	Veg.	Fruits	Pulses & nuts	Dairy	Red meat
TFP growth rate		0.69	0.31	0.70	0.80	3.27	0.76
Initial GDP share		1.42	4.95	1.63	0.74	0.33	1.31
GDP growth	4.02	0.017	0.017	0.017	0.017	0.017	0.017
Agriculture	2.84	0.076	0.067	0.078	0.103	0.076	0.065
Crops	*2.81*	*0.086*	*0.075*	*0.088*	*0.117*	*−0.004*	*−0.005*
Livestock	*2.81*	*−0.002*	*0.001*	*−0.002*	*−0.004*	*0.979*	*0.859*
Industry	3.90	0.002	0.002	0.001	−0.007	0.001	0.003
Agroprocessing	*4.63*	*0.024*	*0.012*	*0.006*	*0.049*	*0.051*	*0.000*
Services	4.48	0.003	0.007	0.003	−0.002	0.004	0.007

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., fruits or red meat), it attracts resources away from value chains with larger processing components (e.g., dairy or pulses & nuts), which may result in very weak (or in some cases, negative) growth in the agroprocessing sector.

In the alternative simulation results (Table A2) with uniform productivity growth, the marginal GDP growth is highest in the large vegetable sector (0.055 percentage points) and lowest in the small dairy sector (0.005 percentage points). This already provides some indication of the potential importance of household income effects on diet quality.

4.3. Food costs and consumption

Table 4 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 from 2017 ICP prices to 2015–16 prices to match the Nigeria GHS Panel 2015-2016 period. Costs are expressed in real terms relative to a fixed model numéraire. Agricultural productivity gains reduce the overall cost of a healthy diet relative to the baseline across all scenarios. As expected, declines are driven largely by price declines in food groups directly linked to the targeted value chains. For instance, the cost of protein foods declines in either the pulse & nut (–2.163 percent) or red meat (–1.778 percent) scenarios. However, it is also evident that the costs of food groups not linked to targeted value chains often increase. For instance, in the vegetable scenario, the cost of the vegetable food group declines by 2.279 percent, but costs of all other food groups increase. This once 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 also in those sectors that do not experience productivity gains. This highlights the importance of using an economywide framework that can capture these trade-offs.

Scenarios that stand out in terms of their large food price impacts are the fruit (–4.190 percent) and dairy (–11.345 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 fruits and 18 percent for dairy foods. These value chain scenarios therefore have a strong impact on the affordability of the reference diet, but demand is severely constrained. Subsequent sharp price declines discourage new entrants into these value chains. A growth strategy targeting such sectors should simultaneously address demand side constraints to avoid significant adverse effects for producers. In the alternative simulation results (Table A2) the largest price decline is observed for vegetables in the vegetable scenario (–7.003 percent), which is driven by the large productivity gain in this sector.

Table 5 reports food consumption gaps. These provide important insights into the drivers of changes in the ReDD index. The first column shows the percentage of people that are deprived in each food group in the baseline scenario by 2025, while the second shows the average deprivation gap by food group. Compared to the initial deprivation rates in Nigeria (Table 2), we notice an appreciable decline in deprivation rates over the simulation period in the baseline, although average deprivation gaps do not change as much.

Table 5 also reports the deviation in deprivation gaps in 2025 from the baseline, in percentage point 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 0.533 percentage points in the vegetable scenario (and by 1.715 percentage points in the alternative simulation results, Table A2). However, in many 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. The effect of value chain growth on overall diet quality is ambiguous because of these substitution effects. The value of the ReDD index lies in its multidimensional nature and the fact that food consumption responses to relative food prices are explicitly considered. Of course, when household incomes rise substantially—by design this is not the case in these scenarios, although it does come into play in the alternative simulation results (Table A2)—income effects will become more important.

Table 4
Simulated diet costs by 2025 *Source: RIAPA model results.*

	Baseline scenario (NGN)	Value chain scenarios: Deviation from baseline diet cost in 2025 (%)					
		Rice	Veg.	Fruits	Pulses & nuts	Dairy	Red meat
Total cost	282.58	−0.085	−0.256	−0.417	−0.880	−2.121	−0.671
Staples	47.20	−0.755	0.098	0.144	−0.072	−0.054	0.136
Vegetables	46.18	−0.100	−2.279	0.095	−0.316	0.154	0.118
Fruits	35.88	0.033	0.120	−4.190	0.011	0.173	0.126
Dairy	42.09	0.179	0.212	0.158	0.140	−11.345	−0.977
Protein foods	94.49	0.058	0.127	0.126	−2.163	−1.455	−1.778
Added fats	16.73	0.124	0.183	0.172	−1.942	0.289	0.178

Note: The baseline cost is expressed in local currency (NGN) per day in survey year (Nigeria GHS Panel 2015-2016) prices. The total cost excludes the cost of discretionary foods. For these reasons the costs are lower than those reported in Table 1.

Table 5
Food consumption deprivation and gaps by 2025 *Source: RIAPA model results.*

	Baseline Scenario in 2025		Value chain scenarios: Deviation from baseline consumption gap in 2025 (%-point)					
	Share of pop. deprived (%)	Average cons. Gap (%)	Rice	Veg.	Fruits	Pulses & nuts	Dairy	Red meat
Staples	9.35	2.07	−0.066	−0.006	0.005	−0.036	−0.006	0.004
Vegetables	90.86	55.38	−0.049	−0.533	−0.003	−0.103	0.004	0.005
Fruits	90.34	72.38	−0.036	−0.022	−1.989	−0.061	0.016	0.014
Dairy	98.59	88.06	0.005	0.003	0.005	−0.005	−1.948	−0.153
Protein foods	79.09	41.76	−0.002	0.000	0.014	−0.482	−0.804	−1.124
Added fats	70.64	28.82	0.001	0.004	0.022	−0.660	0.047	0.027

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. Diet outcomes

Table 6 reports selected diet outcome results. The first part of the table reports the percentage deviation in ReDD-X in 2025 in each scenario relative to the baseline. ReDD-X is 0.933 percent lower in 2025 in the dairy scenario relative to the business-as-usual baseline scenario, and only 0.051 percent lower in the rice scenario. The decline in ReDD-X is consistently larger for urban households, with rural households seeing some of their income gains from increased agricultural output eroded by lower prices for the marketed outputs that they produce.

The second part of the table shows the percentage deviation in ReDD-C in 2025 in each scenario relative to the baseline. Value chain scenarios are ranked similarly as in the case of the ReDD-X index. The largest decline in the ReDD-C index occurs in the dairy scenario (–1.078 percent), and the smallest in the rice scenario (–0.166 percent). However, the fruit and pulse & nut scenarios switch second and third places. Since the ReDD-C algorithm separately accounts for income and own-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 have similar impacts on national household income. The differences that remain relate to differences in income elasticities and household income distribution between scenarios. Own-price effects dominate, especially in the higher-ranked value chains.

In the alternative simulation results (Table A2) the fruit scenario emerges as most effective in reducing diet deprivation (–0.966 percent change in the ReDD-X index). This is partly driven by the decline in fruit costs (–5.837), but the scenario also generates relatively strong household income effects via the change in GDP, which further contributes to the decline in diet deprivation. By comparison, although the dairy scenario results in an appreciable decline in dairy costs (–3.883 percent), income effects are small given the small size of the sector, and hence this value chain now ranks fifth in terms of its effectiveness in reducing diet deprivation.

Table 6
Changes in ReDD-X and ReDD-C from baseline in 2025. *Source: RIAPA model results.*

	Value chain scenarios (ranked)Deviation from baseline ReDD-X or ReDD-C in 2025 (%)					
	Rice	Veg.	Fruits	Pulses & nuts	Dairy	Red meat
ReDD-X						
National	−0.051	−0.192	−0.675	−0.467	−0.933	−0.425
Urban	−0.116	−0.299	−0.814	−0.561	−0.972	−0.458
Rural	−0.021	−0.143	−0.611	−0.424	−0.916	−0.411
Rank	(6)	(5)	(2)	(3)	(1)	(4)
ReDD-C						
National: Total effect (a + b)	−0.166	−0.309	−0.366	−0.724	−1.078	−0.319
Income effect (a)	−0.073	−0.070	−0.042	−0.098	−0.076	−0.069
Own-price effect (b)	−0.092	−0.238	−0.324	−0.626	−1.002	−0.250
Rank	(6)	(5)	(3)	(2)	(1)	(4)

Table A1
Detailed RIAPA commodity listing and mapping to ReDD food groups *Source*: Authors' representation.

Food groups: ReDD	Food groups: diet costing	RIAPA food commodities by sector and subsector
Starchy staples	Cereal grains	Crops (5): Maize | Sorghum & millet | Rice | Wheat and barley | Other cereals | Processing (6): Maize milling | Sorghum and millet milling | Rice milling | Wheat and barley milling | Other grain milling | Other foods
	Starchy roots and tubers	Crops (5): Cassava | Irish potatoes | Sweet potatoes | Other roots | Plantains
Vegetables	Vegetables	Crops (2): Leafy vegetables | Other vegetables | Processing (1): Fruit and vegetable processing
Fruits	Fruits	Crops (2): Bananas | Other fruits
Dairy foods	Dairy foods	Livestock (1): Raw milk | Processing (1): Dairy
Protein sources	Meat, fish, eggs	Livestock (5): Cattle | Poultry | Eggs | Small ruminants | Other livestock | Fisheries (2): Aquaculture | Capture fisheries | Processing (2): Meat processing | Fish and seafood processing
	Pulses & nuts	Crops (5): Pulses | Groundnuts | Other oilseeds | Nuts | Other crops
Added fats	Added fats	Processing (1): Fats and oils
	Added sugars and other, non-essential foods	Crops (4): Sugarcane | Leaf tea | Coffee | Cocoa | Processing (4): Sugar refining | Coffee processing | Tea processing | Beverages
Total: 6	Total: 9	Total: 46 [Crops: 23, Livestock: 6; Fisheries: 2; Processing: 15]

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. Diets may also be impacted indirectly by other policies or investments via their impacts on incomes or 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 optimal or ideal food intakes by food group. Our Reference Diet Deprivation (ReDD) index is a compound measure of the

Table A2
Alterative simulation results: GDP, diet costs, and consumption gaps for a constant productivity growth rate *Source*: RIAPA model results.

	Value chain scenarios Deviation from baseline					
	Rice	Veg.	Fruits	Pulses & nuts	Dairy	Red meat
Simulation shock (%-point change)						
TFP growth rate	1.00	1.00	1.00	1.00	1.00	1.00
Initial TFP growth rate	*0.69*	*0.31*	*0.70*	*0.80*	*3.27*	*0.76*
Initial GDP share (%)	1.42	4.95	1.63	0.74	0.33	1.31
Change in GDP growth (%-point)	0.025	0.055	0.025	0.022	0.005	0.023
Agriculture	0.110	0.213	0.112	0.128	0.024	0.086
Crops	*0.125*	*0.240*	*0.127*	*0.146*	*−0.001*	*−0.006*
Livestock	*−0.003*	*0.002*	*−0.003*	*−0.005*	*0.309*	*1.124*
Industry	0.003	0.006	0.001	−0.008	0.001	0.004
Agroprocessing	*0.034*	*0.037*	*0.008*	*0.062*	*0.018*	*0.000*
Services	0.005	0.021	0.005	−0.003	0.001	0.009
Change in diet cost (%)	−0.122	−0.789	−0.581	−1.090	−0.727	−0.872
Staples	−1.077	0.298	0.200	−0.089	−0.020	0.175
Vegetables	−0.145	−7.003	0.132	−0.391	0.053	0.152
Fruits	0.047	0.363	−5.837	0.015	0.059	0.162
Dairy	0.256	0.652	0.220	0.170	−3.883	−1.288
Protein foods	0.082	0.386	0.174	−2.675	−0.499	−2.299
Added fats	0.176	0.563	0.240	−2.423	0.096	0.231
Change in consumption gaps (%-point)						
Staples	−0.097	−0.018	0.007	−0.044	−0.002	0.006
Vegetables	−0.070	−1.715	−0.005	−0.128	0.001	0.006
Fruits	−0.052	−0.068	−2.845	−0.075	0.005	0.018
Dairy	0.008	0.009	0.006	−0.007	−0.590	−0.202
Protein foods	−0.003	0.001	0.020	−0.605	−0.262	−1.475
Added fats	0.002	0.014	0.030	−0.825	0.015	0.035
Change in ReDD-X (%)						
National	−0.073	−0.616	−0.966	−0.584	−0.289	−0.559
Urban	−0.167	−0.950	−1.163	−0.700	−0.304	−0.601
Rural	−0.030	−0.463	−0.875	−0.531	−0.282	−0.539
Rank (initial rank in parentheses)	6 (6)	2 (5)	1 (2)	3 (3)	5 (1)	4 (4)
Change in ReDD-C (%)						
Total effect (a + b)	−0.239	−0.954	−0.510	−0.896	−0.357	−0.417
Income effect (a)	−0.107	−0.226	−0.061	−0.122	−0.024	−0.091
Own-price effect (b)	−0.132	−0.728	−0.449	−0.774	−0.333	−0.326
Rank (initial rank in parenthesis)	6 (6)	1 (5)	3 (3)	2 (2)	5 (1)	4 (4)

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 reference consumption levels (depth of deprivation). As such, it captures multiple dimensions of diet deprivation in a single indicator. The index can be computed either using food expenditure or calorie consumption data.

The second objective is to showcase an approach for integrating the ReDD index into an economywide model, 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 assess 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. ReDD is therefore one of a range of outcome indicators against which policies can be assessed and ranked using the RIAPA framework.

We use the RIAPA model to compare 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 six agricultural value chains—rice, vegetables, fruits, pulses & nuts, dairy, and red meat—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 or assess the growth potential, but to compare the effectiveness of growth originating in targeted value chains on household diets. By normalizing the GDP effects, scenarios are made to be broadly comparable in that they generate similar increases in national household income.

The dairy, pulse & nut, and fruit value chains emerge as the three most effective at improving diet quality relative to the baseline over the simulation period and per constant unit of growth generated. This top-three 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 declining 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, the own-price effects dominate income effects and hence drive changes in diet quality.

Under scenarios where the impact on relative prices is neutral or where income changes are more substantial, income effects may dominate own-price effects. This is demonstrated with the aid of an alternative set of simulation results where the size effect of sectors is no longer neutralized but a uniform productivity growth rate is applied across all value chains. This results in larger income effects in the vegetable scenario, which combine with price effects to make this value chain the most effective at reducing diet deprivation. Income effects in the small dairy sector are now considerably weaker, thus relegating this value chain to fifth place.

The ReDD index has some limitations. First, as a measure designed to measure food consumption shortfalls, it disregards overconsumption of calories. While it is mathematically possible to combine over- and underconsumption gaps in a single index, it would complicate the interpretation of the ReDD index. A judgement call would also be required to decide in which food groups overconsumption would be considered detrimental to healthy eating and in which they are acceptable. An assessment of overconsumption would further only be plausible with a calorie-based approach as it would be impossible to know whether a household that overspends truly consumes too many calories or simply chooses to buy expensive ones. Simulation analysis in a framework such as RIAPA would also be complicated, especially if a policy (e.g., a cereal price subsidy) simultaneously causes underconsumption to decline and overconsumption to increase. Thus, while we acknowledge limits to the applicability of the ReDD index as a diet quality measure in settings of widespread overconsumption, there are many good reasons not to attempt a modification to the index. Of course, this limitation is not unique to the ReDD index and is common among other measures such as dietary diversity scores and nutrient adequacy indicators. We maintain that in most developing countries underconsumption of nutritious foods and micronutrient malnutrition is still a much larger nutrition problem than overconsumption of unhealthy or highly processed foods, and so the ReDD index is still appealing in such contexts.

Second, global reference diets, such as the EAT-*Lancet* diet (Willett et al., 2019), may not always be suited to a particular country context where cultural, geographical, or environmental factors cause consumer preferences to deviate from what might be considered a global norm. The EAT-*Lancet* diet has also been criticized for being unattainable for most of the world's poor (Hirvonen et al., 2020; Headey et al., 2023), while others have challenged the scientific basis for claims that it can prevent malnutrition and non-communicable disease (Blackstone and Conrad, 2020; Leroy and Cofnas, 2020; Zagmutt et al., 2020). Of course, the ReDD index can also be estimated using other quantitative food-based dietary guidelines, which may be more appropriate in certain contexts. However, in the absence of suitable guidelines—including in Nigeria—the EAT-*Lancet* diet is a useful substitute. The diet is not only globally recognized and accepted, but it serves as an objective optimal or ideal diet that facilitates diet quality comparisons across households, populations, or countries.

Lastly, there are well-documented limitations to the use of household consumption and expenditure survey data for diet analysis (see e.g., Zezza et al., 2017; Fiedler,et al., 2012). This includes limitations around assumptions of the bioavailability of food, a lack of information on intrahousehold allocation of food, and common challenges associated with measurement of food consumption quantities, calorie consumption amounts, or food prices in household surveys. 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 to be a rich measure of diet quality that can easily be computed from readily available household survey data. Although as a diet-based indicator the ReDD index does not allow us to infer nutritional status, it goes beyond score-based diet quality measures in considering both whether a food group is consumed and the extent to which households are deprived within and across food groups. The ReDD index can further be used to compare the quality of diets across households or populations, track changes in diets over time, or, when integrated into an economic model such as RIAPA, to simulate the impact of policies, investments, or external shocks on household diets.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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