Where are nutritious diets most expensive?

Evidence from 195 foods in 164 countries

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Running head: The cost of nutritious diets across countries

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Abstract: Food prices vary widely around the world, depending on the local cost of retail services and supply chains as well as farm supply and the border prices of tradable commodities. This study measures the cost of the most affordable nutritionally adequate diet in each country, relative to the cost of dietary energy and other benchmarks such as national income and poverty lines, so as to identify development paths associated with lower cost access to the nutrients needed for a healthy and active life. We use prices for 195 standardized food and beverage items across 164 countries in 2011 collected by the World Bank's International Comparison Project (ICP), matched with data on these items' composition in terms of 21 essential nutrients and each nutrient's lower and upper limits for a healthy adult woman. Using a subsample of 134 countries for which economic structure data are available, we find that the cost of nutrient adequacy is highest in poorer and middle-income countries, and is higher in countries with a smaller share of workers in the service sector, less urbanization and longer rural travel times to cities, at each level of national income within ICP regions. These results reveal how, controlling for income and region-specific factors, agricultural transformation towards off-farm activities is associated with lower retail prices for nutrient-rich foods. Items such as milk and eggs or fruits and vegetables are often perishable and use specialized supply chains, revealing the important role of post-harvest food systems in the cost of nutritious diets. Results presented here address variation across countries using a standardized global food list, pointing to opportunities for research on temporal and spatial variation as well as the role of additional foods that might fill nutrient gaps at low cost in particular settings.

Where are nutritious diets most expensive?
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Motivation

A long literature argues that higher costs for more nutritious items contributes to poor diet quality and ill health (Darmon and Drewnowski 2015), but price indexes rarely reflect the nutritional value of different foods. Retail prices are routinely used to measure living standards and global poverty rates, and bulk prices of globally traded commodities are used to guide agricultural policy (FAO 2018), while the few existing studies of market prices for nutritious diets use indexes tailored to specific settings such as the United States (Fan et al. 2018) or low-income countries (Deptford et al. 2017). In this paper, we use retail prices together with food composition data and nutrient requirements to measure the cost of a nutritionally adequate diet in every country of the world. This procedure allows for substitution among foods to obtain all essential nutrients needed to maintain long-term health for a representative person. We compare the resulting cost of a nutritionally desirable diet to the cost of a survival diet that meets only daily energy needs, and provide data visualizations plus regression results to describe how the cost of nutritious diets varies with economic development and structural factors including sectoral composition, urbanization, rural infrastructure and access to international trade.

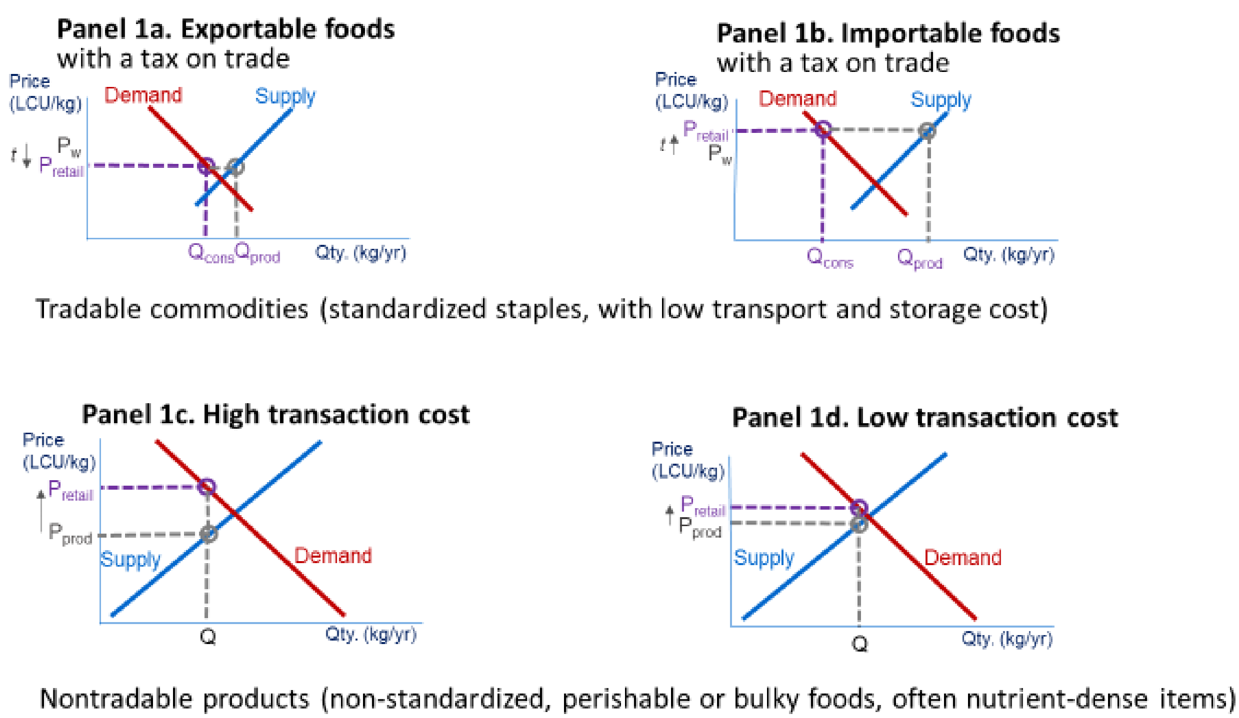
Our work is driven by concerns that agricultural policies and market developments have focused on lowering the cost of starchy staples needed for daily energy, while neglecting supply-demand balances and high prices of the diverse foods needed for lifelong health (Global Nutrition Report 2018). Previous work reviewed by Darmon and Drewnowski (2015) focuses on prices for specific foods and food groups, whereas our approach allows for a location-specific choice of foods to meet nutrient requirements, comparing the cost of the most affordable nutritious diet to the cost of 'empty' calories. The cost of meeting nutritional goals can also be compared with actual food choices, prevailing wages or standard poverty lines (Allen 2017).

The analysis presented here has three principal aims: First, we update existing methods for measuring the cost of nutritious diets, adding macronutrient balance and upper limits for potentially toxic micronutrients as well as minimum requirements to identify the premium to be paid above the subsistence cost of daily energy for the specific mix of 21 essential nutrients at levels associated with long-term health (Institute of Medicine 2006). Second, we demonstrate the empirical feasibility of this approach using retail prices for 195 standardized food and beverage items collected by the International Comparison Project (ICP 2018), matched with their nutrient composition (USDA 2013). Third, we describe international variation in least-cost diets, using data visualizations and regression results to reveal stylized facts about how the cost of nutritious diets relates to economic development and structural transformation based on a variety of measures from World Bank (2018). All prices and diet costs are measured at purchasing power parity (PPP) prices for 2011, allowing direct comparison to the World Bank's international poverty line of US$1.90/day.

Results discussed here build on Allen (2017) and also Masters et al. (2018), addressing global patterns in which foods provide the required nutrients at lowest total cost in each country, and the degree to which each nutrient requirement influences the cost of an overall nutritious diet. We also build on Headey et al. (2017), and Headey, Hoddinott and Hirvonen (2018) who compare food groups using the same ICP data and find systematic differences in the prices of nutrient-dense vegetables and animal sourced foods relative to starchy staples. Those patterns could be explained by a model of price formation in which calorie-dense staples are likely to be tradable commodities whose prices largely depend on access to world markets, while nutrient-dense vegetables and animal-source foods are less easily traded so their prices are more sensitive to the efficiency of local supply chains and retail services.

Hypothesized market mechanisms that could lead to systematic patterns in retail prices for different kinds of food are illustrated in Figure 1. When foods are easily transported and traded, whether they are exportable (Panel 1a) or importable (Panel 1b), this model reveals how competitive markets link local availability to world market prices (P_{world}), which depends in part on export taxes or imports tariffs denoted *t*. When foods are too perishable or bulky for international trade, Figure 1 shows how their local supply-demand balances drive local retail prices (P_{retail}) which depends in part on farm-to-market services and transaction costs which may be large (Panel 1c) or small (Panel 1d).

Figure 1. Models of price formation influencing the cost of a nutritious diet



In this paper, we hypothesize that relative prices among different kinds of food might vary systematically with per-capita income and a country's economic structure, driven by the market forces shown in Figure 1 for both tradable and nontradable items. Bennett's law that demand for diverse foods beyond starchy staples expands with income faster than demand for other foods (Clements and Si 2017) will influence the fraction of foods that are exportable or importable in any given country, and will influence the price of nontradables directly through supply-demand balances. More nutrient-dense fruits, vegetables and animal-source foods may be especially sensitive to the cost of post-harvest services along the farm-to-market supply chain, compared to cereal grains and other starchy staples that are easier to store and transport (Maestre et al. 2017). From those observations we draw on Reardon and Timmer (2012) and the model in Figure 1 to hypothesize that, at each level of per-capita income, countries might have a relatively lower cost of essential nutrients when they have:

1. A larger service sector, offering more horizontal competition but also more vertical integration in post-harvest handling;
2. Greater urbanization, which concentrates consumers in space and allows for scale economies in farm-to-market supply chains;
3. Easier rural transportation and access to electricity, thereby improving the efficiency of transport and storage from farm to market; and
4. Easier access to international markets, including lower import tariffs, for tradable items that enter local food systems.

These four hypotheses refer to stylized facts about long-run equilibria as shown in Figure 1. In the short run and for any particular food, many diverse factors would intervene to shift supply and demand, and those factors would also influence our macroeconomic variables such as urbanization and service orientation of the economy, roads and electrical infrastructure, and trade policy. Our aim in this paper is not to isolate a causal relationship with any one variable, but to provide an initial test of whether systematic patterns exist across countries in a single year. Other work within countries and across time can help identify the causes and consequences of food price changes, addressing questions such as whether infrastructure can moderate seasonality in the prices of nutritious foods (Bai et al. 2018), or the role of specific kinds of supply chains for particular food groups (Headey et al. 2018).

Methods

To measure the cost of a nutritious diet across countries, we compute three major types of price indexes that meet estimated requirements for a median healthy woman of reproductive age. This work builds on the formulation of least-cost diets pioneered by Stigler (1945), which has long been used to recommend combinations of foods that meet health needs for low-income people in industrialized countries (Cofer et al. 1962, Gerdessen and De Vries 2015, Parlesak et al 2016, Maillot et al. 2017) as well as the general population in lower-income settings (Optifood 2012, Deptford et al. 2017, Vossenaar et al. 2017). Our application here uses the least-cost diet to compare the performance of food systems in delivering a balance of essential nutrients at low cost, extending O'Brien-Place and Tomek (1983) to international comparisons. For this purpose, we include upper limits on some nutrients to avoid excesses associated with chronic diseases, in addition to the lower bounds needed to avoid undernutrition in low-income settings as in Chastre et al. (2007), Omiot and Shively (2017) and Masters et al. (2018).

To address cross-country differences in access to nutritious foods, our principal measure is the Cost of Nutrient Adequacy (CoNA), defined as the minimum cost of foods that meet all known requirements for essential nutrients and dietary energy requirements for a woman of reproductive age. We then compare this to the Cost of Caloric Adequacy (CoCA), defined as the price of the least-cost foods that are required to meet the caloric needs. To measure CoNA, we use the price of each food and its nutrient content relative to lower bounds and upper limits needed for daily energy and long-term health:

(1) $\text{CoNA} = \text{min.} \{ C = \Sigma_i p_i \times q_i \}$

Subject to:

(2) $\Sigma_i a_{ij} \times q_i \geq EAR_j$

(3) $\Sigma_i a_{ij} \times q_i \leq UL_j$

(4) $\Sigma_i a_{ij} \times q_i \leq AMDR_{j,upper} \times E / e_j$

(5) $\Sigma_i a_{ij} \times q_i \geq AMDR_{j,lower} \times E / e_j$

(6) $\Sigma_i a_{ie} \times q_i = E$

(7) $q_1 \geq 0, q_2 \geq 0, q_3 \geq 0, \ldots, q_i \geq 0$

In this notation, the quantity of the j^{th} nutrient in food i is denoted a_{ij}, which multiplied by its quantity consumed (q_i) must meet the population's estimated average requirement (EAR) for nutrient j, while remaining below upper limits (UL) for micronutrients and within a range for macronutrients determined by acceptable macronutrient distribution ranges ($AMDR_{lower}$ and $AMDR_{upper}$) as percentages of daily energy needs (E), at lowest total cost given all prices (p_i) within the further constraint of overall energy needs (E). The reference number e_j is the energy density of macronutrients, equal to 4 kcal per gram of protein or carbohydrate, and 9 kcal per gram of lipid. This provides a lower bound on the cost of meeting all nutrient constraints, which we contrast with the cost of meeting only the daily energy constraint in equation (6), which we call the cost of caloric adequacy (CoCA). CoNA minus CoCA is the additional cost above daily subsistence needed to sustain future health, expressed either in absolute terms in US dollars per day at real purchasing power parity (PPP) prices, as a ratio or in logarithmic form.

For both CoNA and CoCA we report the foods needed in each country to meet nutritional needs at lowest cost. A key feature of our approach is to constrain nutritious diets to meet not only the EARs needed to avoid undernutrition, but also a balanced diet in terms of the three macronutrients through the AMDR, and upper bounds on micronutrients for which excess intake could be harmful. We further constrain the overall energy balance not to exceed the standard benchmark of 2,000 kcal/day. The resulting CoNA and CoCA values provide the lowest costs of meeting nutritional and caloric requirements, respectively. These lowest bounds, however, will likely differ from what any group might actually consume (for which we would use a consumption price index), or should consume (in the sense of a recommended diet). Diets that are actually consumed by individuals in these countries will likely exceed or fall short of any given nutritional standard given that local eating habits and cultural norms vary tremendously across countries and also dictate what a locally acceptable "normal diet" is in a given context.

Besides the computation of these price indexes, we also report the cost of each nutrient which is reflected in their respective shadow prices. Shadow prices of each nutrient is defined as the marginal cost associated relaxing each constraint by one unit. Since our objective is minimizing cost, a positive shadow price indicates an increase in CoNA and CoCA with a unit increase in the constraint:

$$SP_j = \frac{\partial C^*}{\partial (EAR, UL, AMDR)_j^+}$$

where C* denotes the minimum cost of the CoNA diet, SP_j is the shadow price of nutrient j (or daily dietary energy), and $(EAR, UL, AMDR)_j^+$ refers to a one unit increase in the requirement constraint of nutrient j (EAR and UL for micronutrient constraints, AMDR for macronutrient constraints and just EAR for energy threshold). As the units of measure for the constraints may differ by nutrient, we construct a semi-elasticity of shadow prices denoted by SP' and defined as increment in the CoNA diet when the constraint is increased by 1%:

$$SP_j' = \frac{\partial C^*}{\% \Delta (EAR, UL, AMDR)_j^+}$$

Calculations for all equations were completed in R and resulting index values exported to Stata 15 or Excel for visualization purposes, with model code and data for replication posted online at the project website referenced in this paper's acknowledgements.

Data

Our food price data comes from the World Bank's International Comparison Program (ICP), an initiative associated with the United Nations Statistical Commission to compare purchasing power and living standards across countries (ICP-World Bank, 2018). The mandate of the ICP includes collecting retail prices for a list of highly standardized goods and services that are widely consumed across countries. For the 2011 round of ICP data, this list includes 201 food items for 177 countries, although not all items are found in every country and not all ICP countries have data that can be compared internationally. Using individual item prices in local currency units from the World Bank, we generated an estimation sample with 20,741 observations from 164 countries after removing all countries with less than 500,000 people to limit their potential influence on our visualizations and hypothesis tests, removing three additional countries (Belarus, Zambia and Jordan) due to apparent typographical errors in the dataset we received, whereby prices of several food items were implausibly high (i.e. exceeding 150 $/kg in PPP terms), and also dropping Taiwan-China as it does not have a purchasing-power parity (PPP) exchange rate in the World Bank database, which is required for international comparison of food costs relative to the cost of all other goods and services consumed in that country. Descriptive statistics on these prices are provided in our online annex of supplemental information, along with model code for replication of our results with other datasets.

A key limitation of ICP data for measuring the cost of nutritious diets is that only standardized foods are included, omitting products that are consumed in only one or a few countries such as the Ethiopian false banana (enset), or foods that are sold in diverse forms of different quality at specific locations such as local fish, fruits, leguminous grains and some dark green leafy vegetables such as cassava leaves. A second limitation of ICP data is that 2011 was a somewhat unusual year for food commodities, as the cost of some internationally traded items such as rice was higher than in proceeding and subsequent years. Both concerns make our CoNA and CoCA estimates an upper bound on the true measure, which would be lower if these foods actually provided essential nutrients at lower cost than the results we obtain.

To calculate the nutritional content of each item, we match its description in the ICP data with test results recorded in the U.S. National Nutrient Database for Standard Reference (USDA, 2013). Out of the 201 food items found in the ICP price data, six were dropped due the absence of clear correspondence to any USDA item. The omitted foods are described by the ICP as sandwich biscuits/cookies, black pomfret, malt vinegar, baby food, and baby cereals. Our procedure also drops mineral water from analysis, since it does not contribute nutrients for which there is a lower bound or upper limit in our least-cost diets. A detailed list of all 195 food items with their respective nutrient compositions is provided in the annex of supplemental information.

The third kind of data needed to calculate CoNA and CoCA are nutrient requirements, for which we use the estimated average requirements (EARs) of a typical adult woman of reproductive age (19-30) with tolerable upper intake level (UL) for micronutrients and acceptable macronutrient distribution ranges (AMDR) for macronutrients, as specified in the Dietary Reference Intake (DRI) developed by the U.S. National Academies of Sciences, Engineering and Medicine of the United States (Institute of Medicine, 2006). All three types of constraint (EAR, UL and AMDR) refer to usual daily intake. EAR is defined as the average daily nutrient intake level estimated to meet requirements at least half of all individuals in an otherwise healthy population, after adjusting for age, sex, height and weight, physical activity and pregnancy or lactation. The main alternative to EARs is the DRI's recommended dietary allowance (RDA), which adds two standard errors of the estimated uncertainty or biological variation to meet estimated needs for 97.5 percent of an otherwise healthy population. RDAs are used primarily to advise individuals or set food rations to ensure that a given person's needs are met, whereas EARs are preferred for population-level analyses regarding the whole distribution as characterized by the median person at each place and time. Both refer to the lower bounds on essential nutrients, defined as compounds that cannot be synthesized in the body but are needed for human health. Some of these nutrients also have an upper limit (UL) beyond which further intake is associated with adverse effects. Also, among the macronutrients that supply dietary energy (carbohydrates, protein and fats), the DRIs provide an average macronutrient distribution range (AMDR) for the fraction of energy from each source associated with reduced risk of metabolic conditions such as diabetes and other conditions linked to macronutrient imbalances. The annex of supplemental information provides a complete list of all EAR, UL and AMDR constraints used as criteria for a nutritious diet.

Our aim in this study is to establish stylized facts about how the cost of nutritious diets varies across countries, testing for associations with income and other characteristics of a country's development path. For this we draw on the World Development Indicators database compiled by the World Bank (2018), plus a geographic database maintained by IFPRI that matches rural population density at each location with spatial data on rural infrastructure (IFPRI 2018a) and another IFPRI database on international trade (Bouët et al., 2017). To test the specific hypotheses described in our motivation, the variables we use are gross national income (GNI) per capita, measured in US dollars at purchasing power parity (PPP) prices in 2011, and four indicators for each of our principal hypotheses: urbanization, defined here as the share of the population living in urban areas as defined by national authorities, from World Bank (2018); service orientation, defined as the fraction of the country's gross domestic product derived from its services sector as opposed to agriculture, mining or manufacturing, also from World Bank (2018); rural transportation infrastructure, defined as average travel time for rural people to reach the nearest city with more than 50,000 people, from IFPRI (2018a) and rural electrification, defined as the share of the rural population with access to an electricity grid, also from IFPRI (2018a); and finally the country's access to international trade, defined as the country's average duty applied on food imports from Bouët et al. (2017). These variables were chosen primarily for their a priori correspondence to the hypotheses that motivate our study, narrowed further to limit reductions in sample size caused by data availability. This specific list of variables results in a final estimation sample of 134 countries. Our annex of supplemental information provides a detailed set of summary statistics for them and for all 164 countries with price data.

Cost of nutrient adequacy by region and level of national income

Table 1 below summarizes results by major geographic region and income categories, as mean levels of CoNA and CoCA in each country grouping as defined by the ICP.

Table 1. CoNA and CoCA by geographic region used for hypothesis tests

		N	CoNA	CoCA	CoNA-CoCA
Income categories	Low income	32	1.79	0.66	1.13
	Lower middle income	38	1.99	0.65	1.33
	Upper middle income	42	1.99	0.53	1.46
	High income	52	1.83	0.59	1.24
Geographic regions	East Asia & Pacific	19	2.14	0.57	1.57
	Europe & Central Asia	44	1.76	0.43	1.33
	Latin America & Caribbean	35	1.47	0.59	0.89
	Middle East & North Africa	10	1.40	0.80	0.60
	North America	3	1.86	0.96	0.90
	South Asia	7	2.24	0.64	1.60
	Sub-Saharan Africa	46	1.53	0.61	0.92
Worldwide		164	1.94	0.60	1.34

Note: Income categories are from the World Bank, geographic regions are as defined in the ICP.

As shown in Table 1, levels of CoNA are generally somewhat lower than the World Bank's $1.90 poverty line derived from actual expenditure patterns, while CoCA is in the range of $0.60/day associated with survival. With regards to income, CoNA increases with income and falls back to lower levels for high-income countries while CoCA starts to fall at a relatively lower income level. Looking across regions we see substantial variation in both measures, with

CoNA being particularly high in South Asia and the Pacific ($2.24), followed by East Asia and Pacific ($2.14). In our hypothesis tests, we use indicators for each of these regions to absorb any fixed effects associated with their agroecological or cultural features, and focus on differences between countries within regions.

Variation within regions can be seen in Figure 2, revealing hotspots of higher CoNA inside Central America and Africa, Asia and Russia, and differences between neighboring countries. Our hypothesis tests will address these differences using the characteristics of each national economy described in our data section. Table 2 presents the summary statistics of the main development indicator variables that we used for testing associations of the price indexes with different characteristics of a country's development path.

Figure 2. Spatial variation in the cost of nutrient adequacy for 164 countries in 2011 (US$/day)

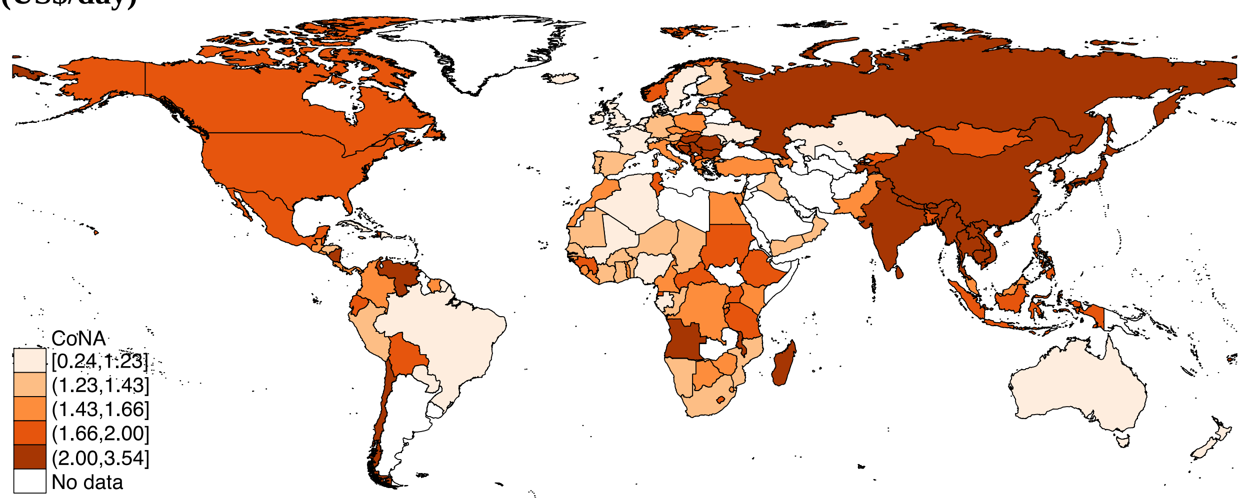


Table 2. Descriptive statistics of structural variables used for hypothesis tests

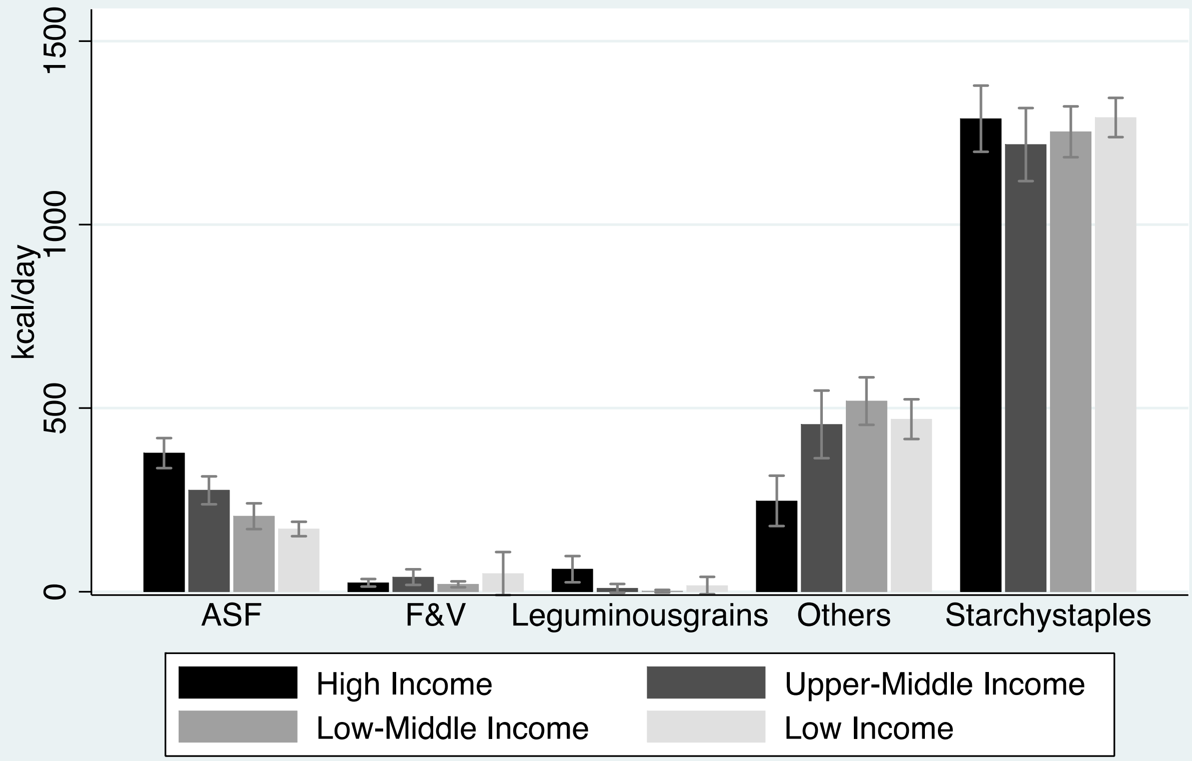
	N	Mean	Std. Dev.	Min	Max
Income (log GNI per capita, PPP adjusted, 2011 Int. $)	134	9.08	0.93	6.51	11.32
Service sector size (share of labor in services, %)	134	46.26	17.28	6.10	85.41
Urbanization (share of population in urban areas, %)	134	51.43	20.16	10.91	100.00
Rural transport (log travel time to nearest city of > 50k pop.)	134	6.22	0.98	4.16	8.12
Rural electrification (share of rural pop. with access in 2011, %)	134	77.37	29.26	0.29	100.00
Trade access (average duty applied on imports, ad valorem)	134	0.20	0.12	0.01	0.64

To visualize which combinations of foods provide needed nutrients at least cost, Figures 3 and 4 show the mean and standard deviation of each food group's contribution in countries at each level of income and major region. Reading Figure 3 from left to right provides suggestive evidence that animal source foods contribute a smaller fraction of the least-cost diet at lower incomes, while fruits and vegetables may be more important as least-cost nutrient sources in lower-income countries. Moreover, we see that large portion of the energy comes from starchy staples across all income levels. Figure 4 reveals regional differences that may not correspond to income level, as the Africa and the Middle East level has the lowest mean contribution from animal source foods, while Europe and Central Asia as well as North and Latin America have the largest. The difference is made up in starchy staples, which play a relatively small role in least-cost diets for the Asia-Pacific region.

The nutrients whose constraints add the most to total cost are shown in Figure 5 and 6. Both show that costs would change primarily with variation in the need for total energy, calcium and folate, while a smaller role is played by requirements for magnesium, zinc, Iron and several vitamins (C, B6 and B12). Differences by income level in Figure 5 are quite striking, as needs for total energy has the greatest link to least-cost diets in middle income countries. There is also a remarkable difference in the role of folate requirements by income in Figure 5 versus region in Figure 6, as folate plays a small role in diet cost for the high income countries, but a large role in the Asia-Pacific region. This difference is due to industrial fortification of low-cost foods that enter the least-cost diet in high-income countries, but not elsewhere and do so to a lesser extent in the Asia-Pacific region. Figure 7 shows that CoNA is most sensitive to changes in the upper bound of the AMDR for carbohydrate followed by the upper AMDR bound for lipids and the lower AMDR bound for protein. However, the upper AMDR bound for protein was never binding.

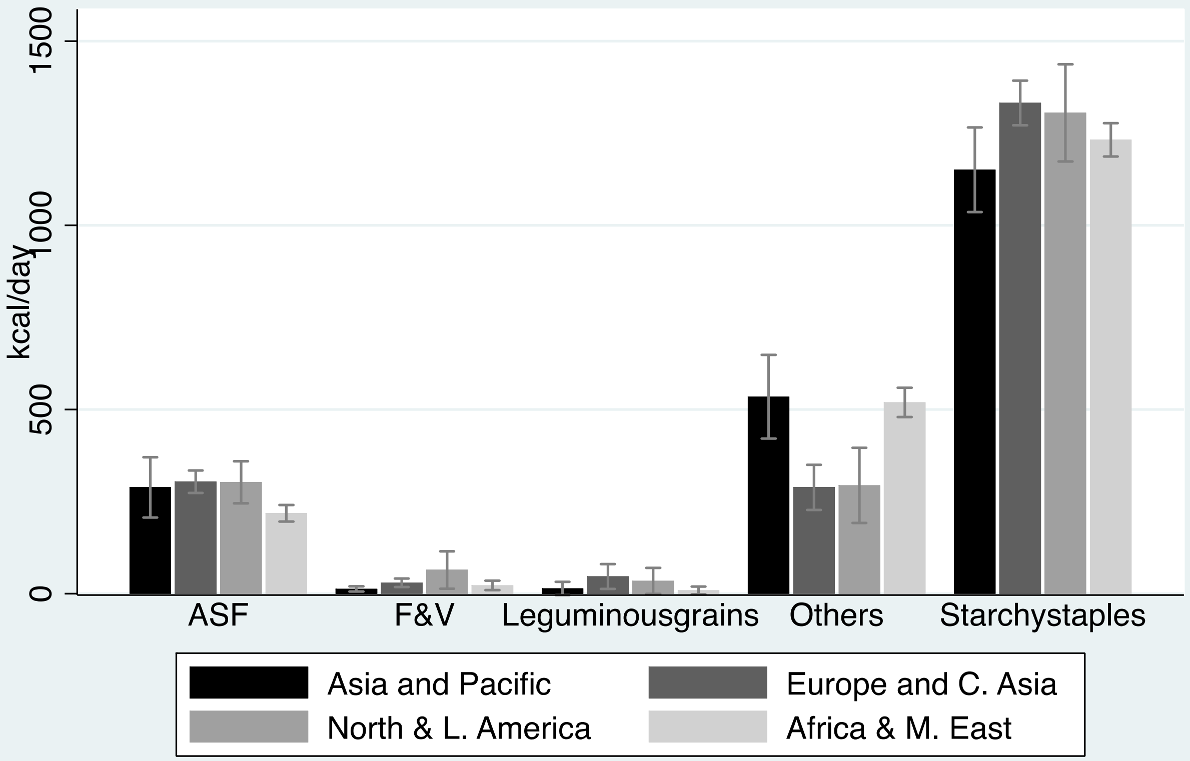
Patterns shown in Figures 3-7 suggest important roles for a wide variety of factors affecting the cost of adequate nutrients across countries. To identify links between these factors and a country's economic development, we begin with the possibility of an inverted-U curve with per-capita income as suggested by Figures 3 and 5, then test for additional links with structural features at each income level as suggested by Figures 8 and 9.

Figure 3. Foods included in least-cost diets, by food category and income level (kcal/day)



Note: ASF- Animal Sourced Foods and F&V- Fruits & Vegetables
Six outlier countries were excluded from our analysis i.e. Bahrain, Saudi Arabia, Qatar
United Arab Emirates Lithuania and Uruguay making the total number of countries analyzed 164

Figure 4. Foods included in least-cost diets, by food category and major region (kcal/day)



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Six outlier countries were excluded from our analysis i.e. Bahrain, Saudi Arabia, Qatar, United Arab Er
Lithuania and Uruguay making the total number of countries analyzed 164

Figure 5. Semi-elasticity of diet cost by nutrient and country income level (US$/pct change)

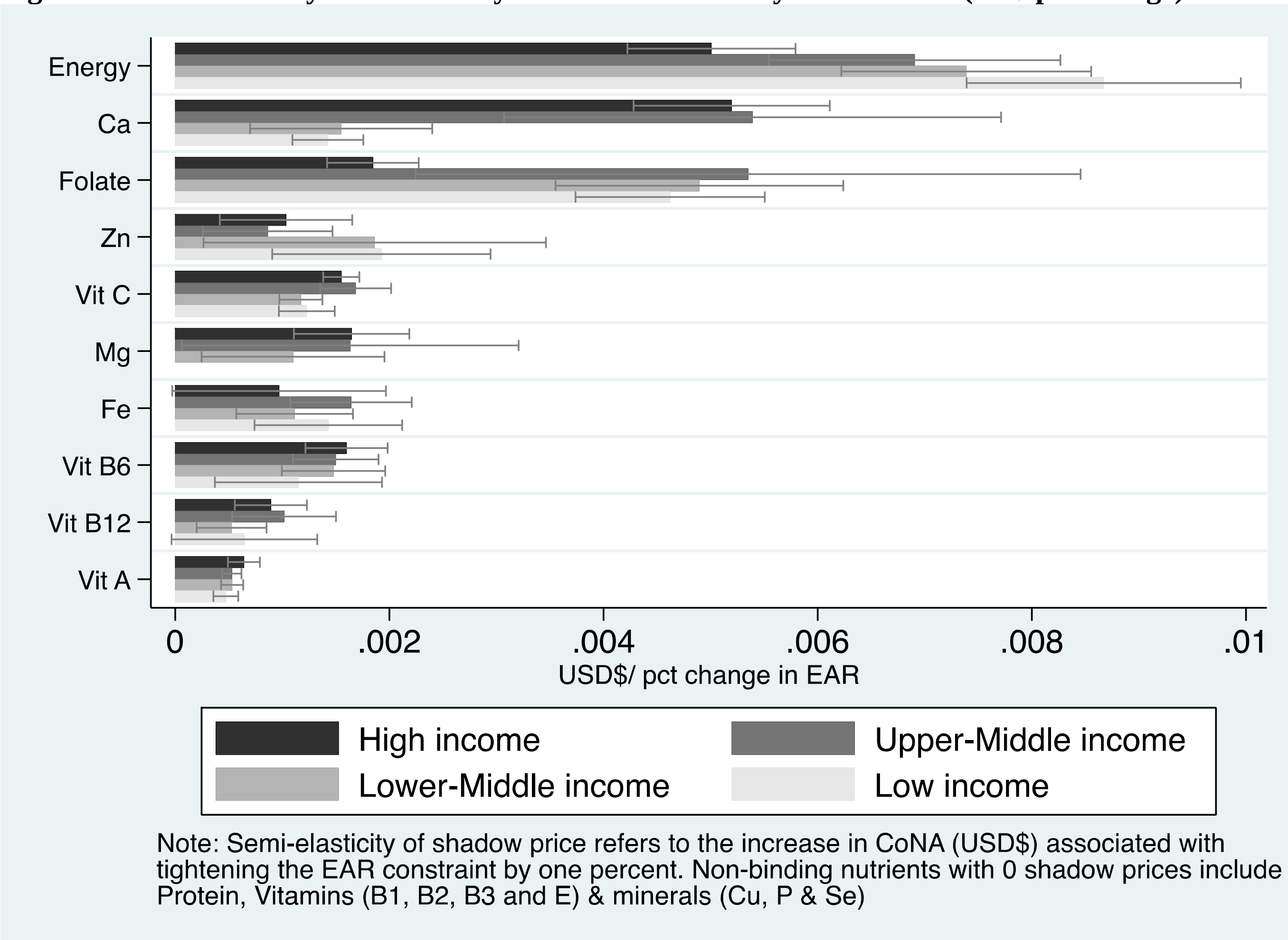
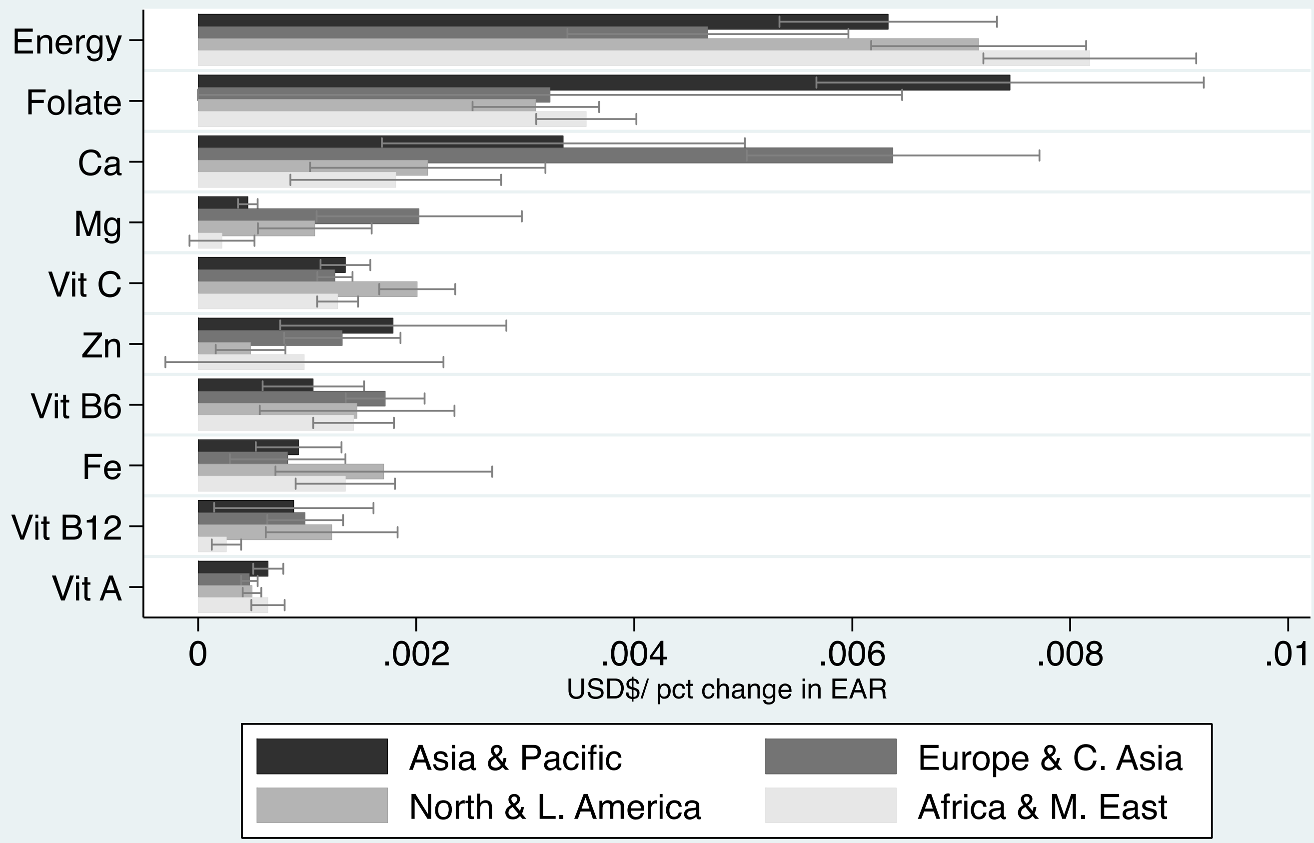
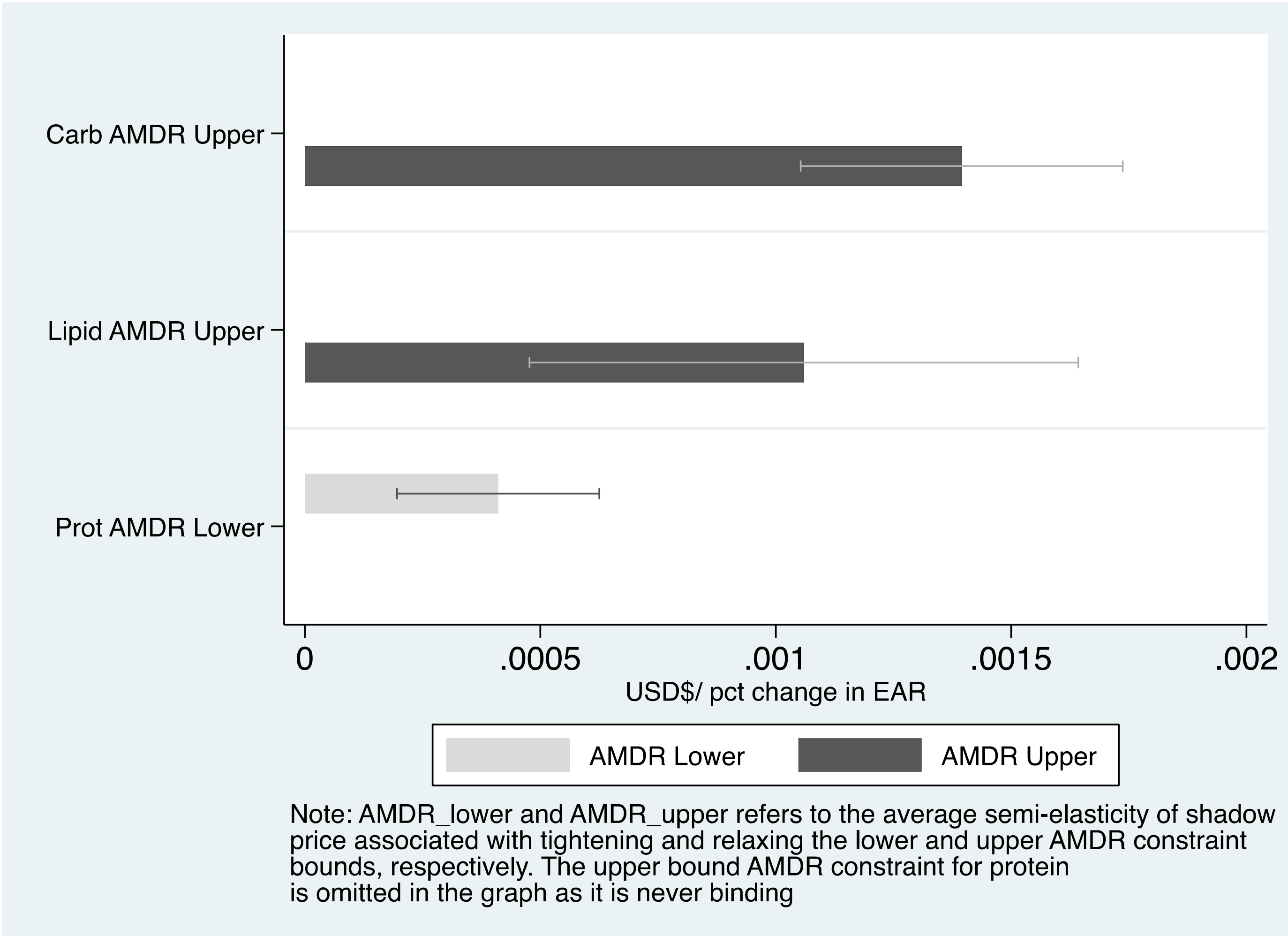


Figure 6. Semi-elasticity of diet cost by nutrient and region (US$/pct change)



Note: Semi-elasticity of shadow price refers to the increase in CoNA (USD$) associated with tightening the EAR constraint by one percent. Non-binding nutrients with 0 shadow prices include Protein, Vitamins (B1, B2, B3 and E) & minerals (Cu, P & Se)

Figure 7. Semi-elasticity of diet cost by macronutrient balance constraint (US$/pct change)



Stylized facts and hypothesis tests

To test for patterns in how the cost of nutritious diets varies across countries, we begin with national income and then consider variations in economic structure at each income level. Figure 8 uses three-letter country codes to show each observation, for CoNA (in black) and CoCA (in gray), with a LOWESS smoother to illustrate their local means at each level of income, and a horizontal guideline for the World Bank poverty line at $1.90. Figure 8 does the same for each country's CoNA-CoCA premium, measuring the additional cost of nutritional adequacy above day-to-day subsistence.

Figure 8. Cost of nutrient adequacy (CoNA) and calories (CoCA) by income level (US$/day)

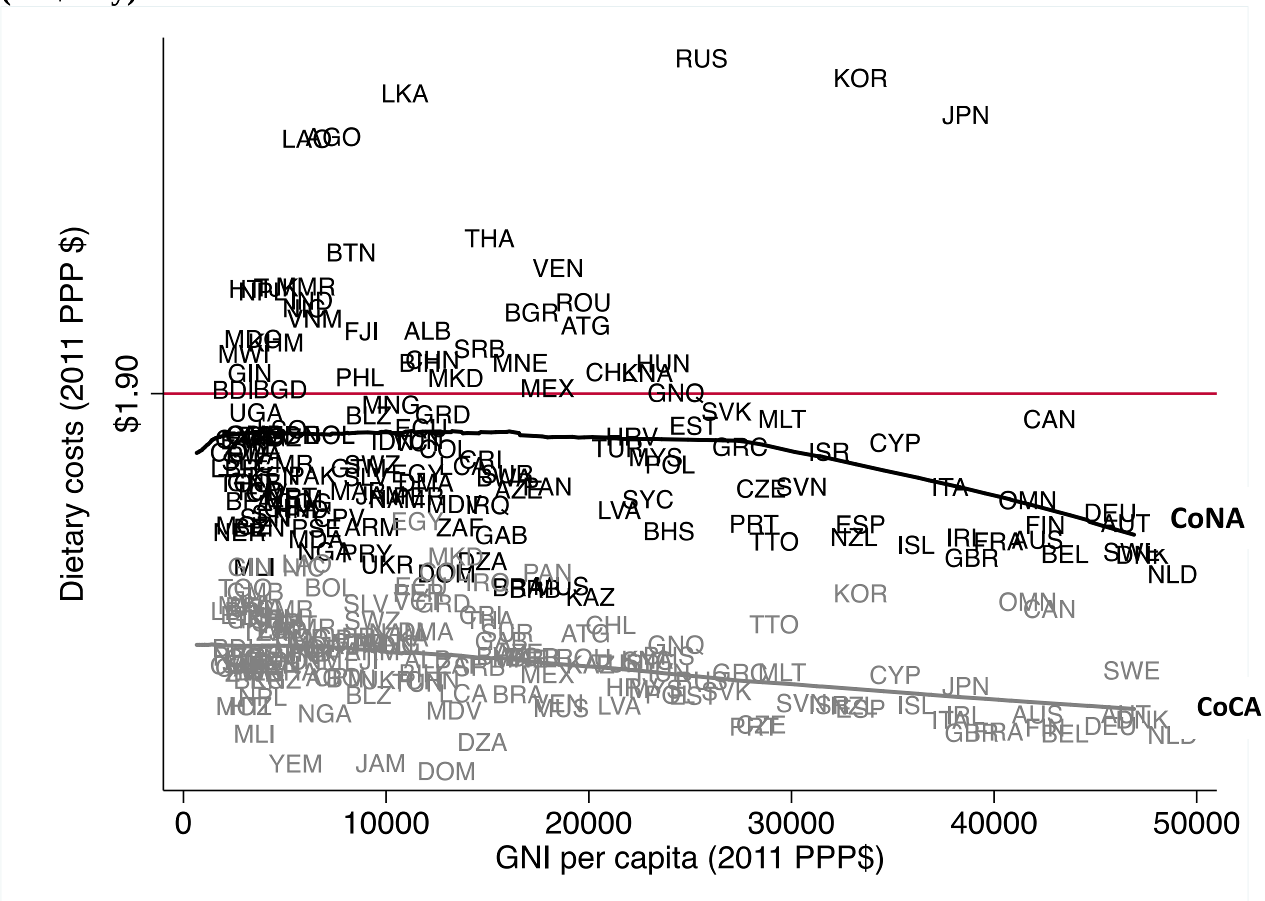
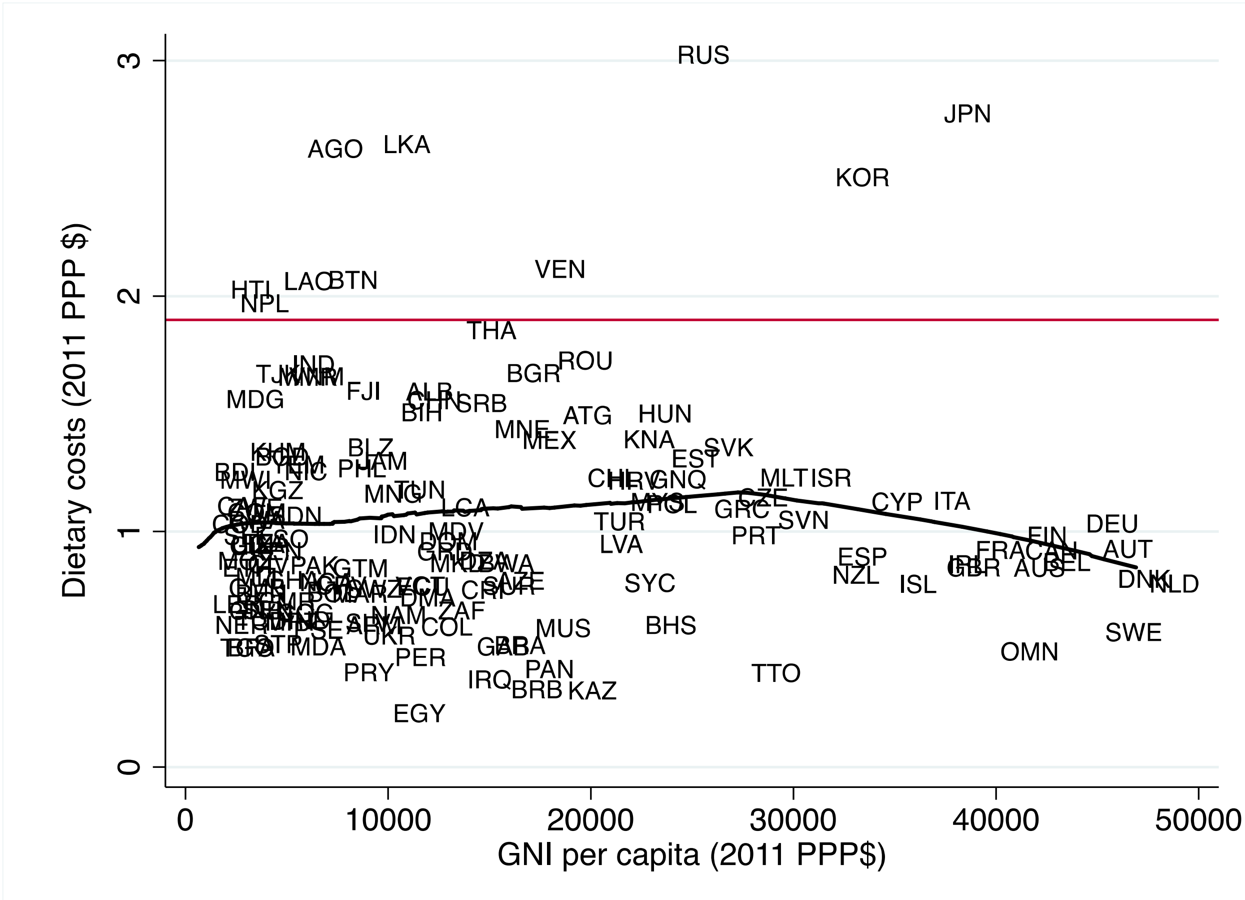


Figure 8 reveals that CoNA clusters around or above $1.90/day in poorer countries, and is generally lower in countries with higher levels of national income. Outliers are clearly identifiable, revealing the specific countries that account for regional differences shown in Table 1, with notably high cost of nutrients in Eastern Asia at all income levels. The pattern for CoCA also shows higher prices in poorer countries, with the smoothed mean ranging from approximately $0.70 in the lowest-income countries to approximately $0.50 in the highest. Comparing both CoNA and CoCA to the World Bank's poverty line of $1.90, it is clear that in the poorest countries caloric adequacy alone would require roughly half the household budget of a household living at that poverty line, while nutrient adequacy generally costs close to the global standard for severe poverty. Nutrient adequacy can be obtained for less than $1.90/day in some poor countries, but is generally available at that price only in richer countries where very few people live at such low income levels (Ferreira et al. 2016).

Our principal finding so far is that both CoNA and CoCA are lower in richer countries. Figure 9 charts each observation and a LOWESS smoother for the CoNA-CoCA premium relative to the $1.90 threshold, revealing wide variation and a similar pattern by which people in poorer countries generally face higher prices for essential nutrients relative to calories.

Figure 9. Premium for nutrient adequacy above daily calories (CoNA-CoCA, in US$/day)

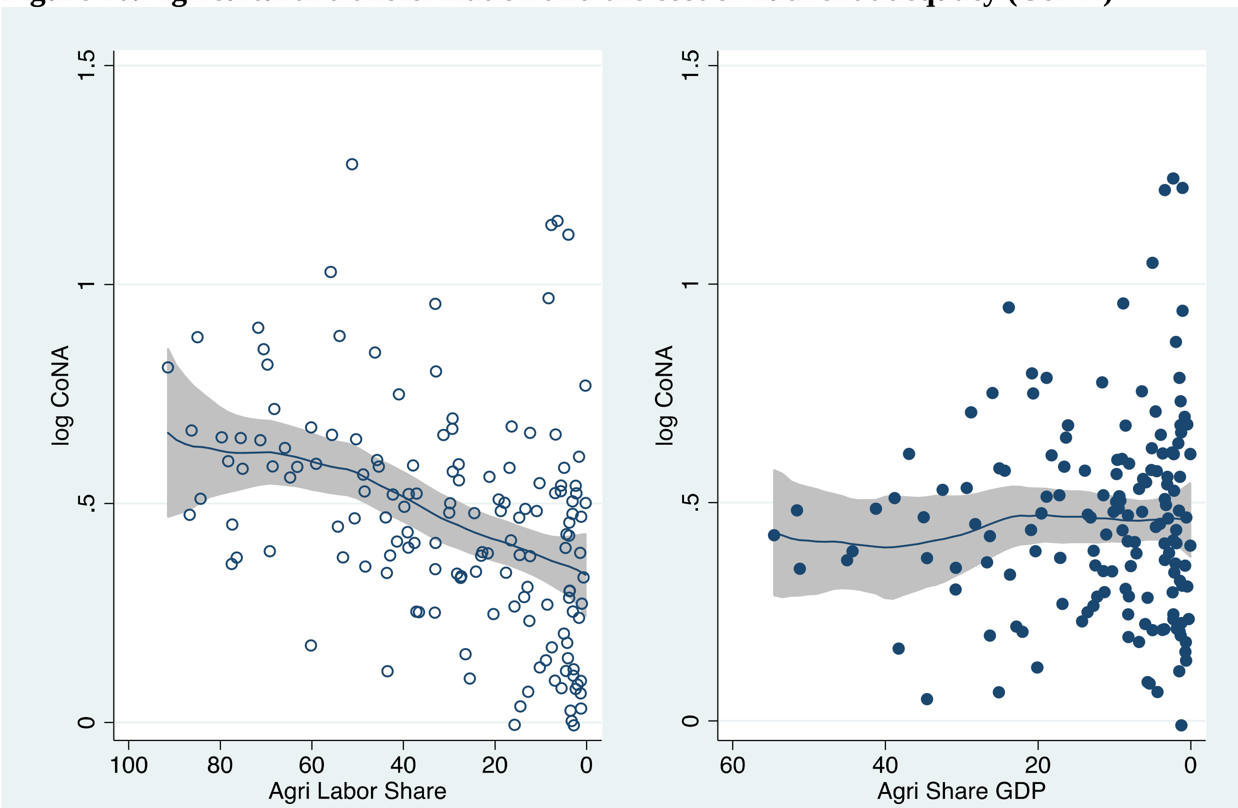


Variation in the cost of nutrient-dense foods across countries as shown in Figures 8 and 9 could be artifacts of our methodology, including especially limitations explained in our data section regarding the absence of ICP prices for local foods that are not internationally comparable. If omitted products like local beans or vegetables were locally available at sufficiently low prices relative to their nutrient density, the true CoNA would be lower. Other studies address this question using a variety of location-specific datasets in Africa, as described in Masters et al. (2018). Our focus here is on access to the specific list of 195 internationally-comparable foods in the ICP data, particularly to investigate whether specific aspects of economic development associated with the patterns we see.

The central hypothesis motivating our work is that post-harvest food systems, for both internationally traded commodities and non-tradable goods and services, play an important role in the cost of more nutritious foods. Using a standard economic model of price formation illustrated in Figure 1, structural factors such as urbanization, service-sector development and rural infrastructure as well as access to imported commodities could all drive retail prices and the cost of meeting nutrient needs, in addition to regional geographic factors affecting agricultural supply and consumers' food preferences. The core intuition for these hypotheses is that nutrient-dense foods are often perishable, so their retail prices are more sensitive to variation in post-harvest services than calorie-dense cereal grains and other staples. Marketing systems for dairy, eggs and other animal sourced foods, as well as fruits and vegetables or other nutrient-dense foods may require cold storage and more rapid distribution, implying lower relative costs in countries whose economic development path favors access to efficient post-harvest services.

Agriculture is the source of both nutrient-dense foods and starchy staples, but a central feature of structural transformation is how increasing productivity in any sector shifts activity away from agriculture towards other sectors, including agricultural marketing systems (storage, transportation, processing). Greater concentration of consumers in urban centers may further increase the density of agricultural marketing systems, lowering the cost of nutritional versus caloric adequacy. For these reasons, at each level of national income, for a given set of agroecological conditions and food preferences, countries with more structural transformation out of farm production and towards post-harvest handling and other sectors may offer lower prices for nutrient-dense foods. Figure 10 begins to point in this direction, presenting semi-parametric regression evidence that the departure of labor from agricultural production is strongly associated with reduction in CoNA, while the share of agriculture in GDP is less relevant.

Figure 10. Agricultural transformation and the cost of nutrient adequacy (CoNA)

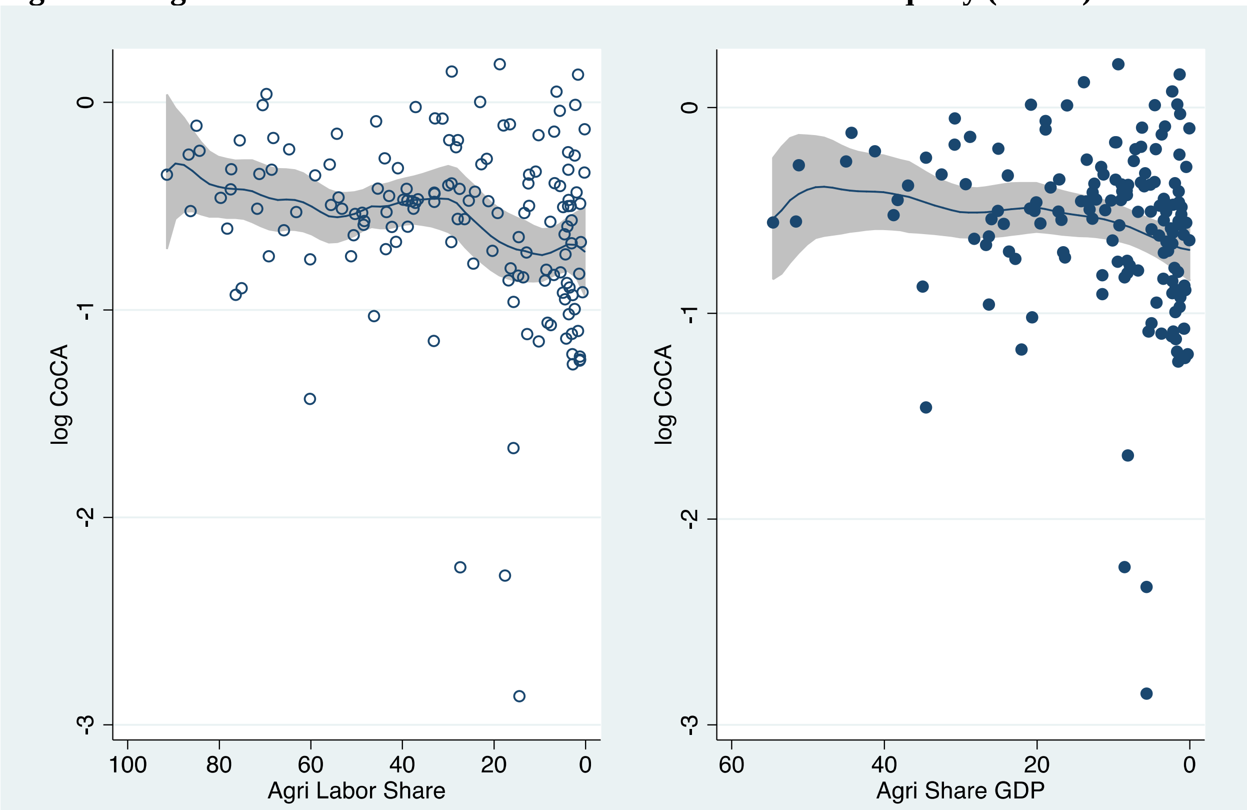


Note: Data shown are residuals and semi-parametric estimates of the mean and its 95% confidence interval after controlling for GNI, GNI squared and fixed effects for each ICP region.

The results shown in Figure 10 control for national income in quadratic form, and use indicator variables to absorb the differences in agroecology, culture and data-collection systems associated with each ICP region (Deaton 2010). We are particularly concerned that ICP surveys may systematically exclude particular foods consumed in specific regions, with the possible result that CoNA would be biased upward in those settings. We use fixed effects at the level of ICP regions to absorb any such variation, so results from here onwards refer specifically to cross-country variation within these regions. We also control for national income so that the effect shown in Figure 10 links CoNA specifically to agricultural transformation, in the sense of farm labor productivity that allows workers to shift out of agriculture independently of agriculture's share in total GDP.

The link between CoNA and agricultural transformation shown above contrasts sharply with Figure 11 below, which repeats the same semi-parametric regression for CoCA. Finding that labor migration from agriculture is less closely linked to CoCA than CoNA is consistent with the notion that labor moving into agricultural marketing services would disproportionately benefit the value chains required for marketing more perishable commodities.

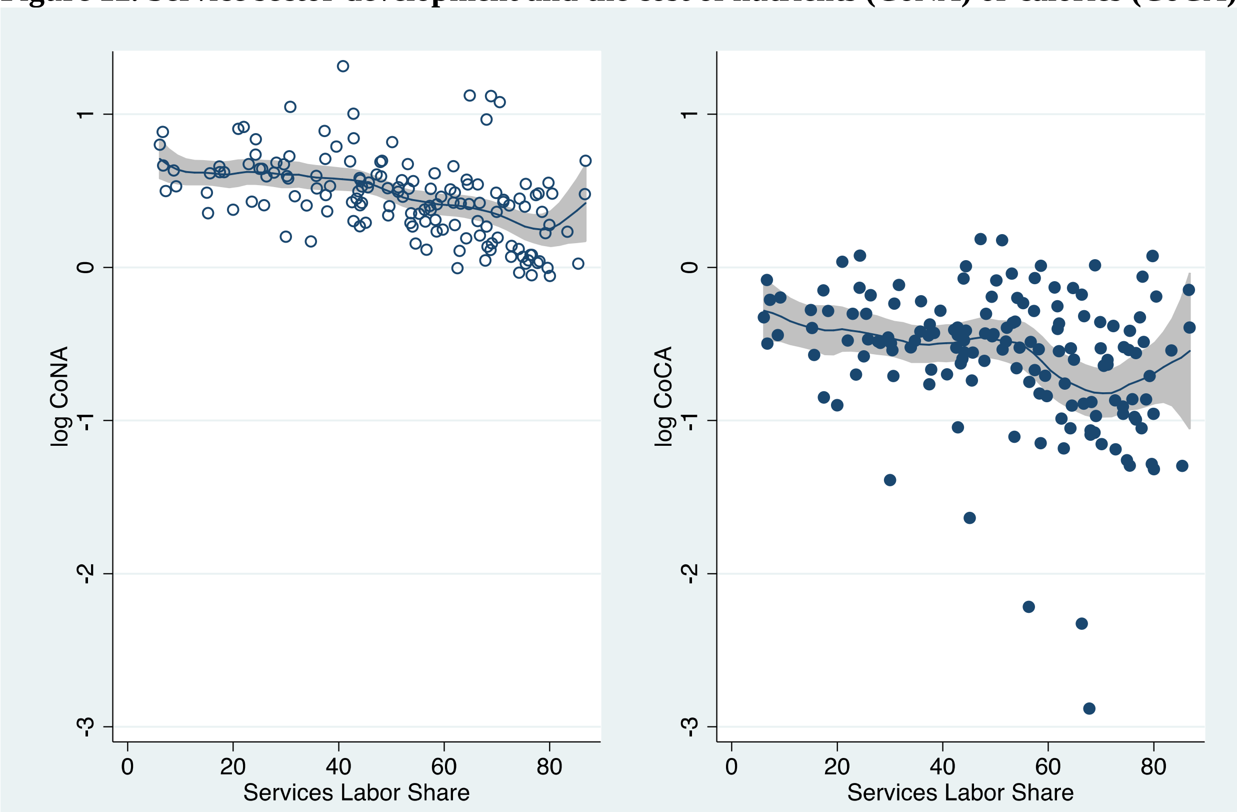
Figure 11. Agricultural transformation and the cost of caloric adequacy (CoCA)



Note: Data shown are residuals and semi-parametric estimates of the mean and its 95% confidence interval after controlling for GNI, GNI squared and fixed effects for each ICP region.

Figure 12 views this transformation from the perspective of the service sector. In this case, we apply the same semi-parametric analysis to a comparison of how labor movement into services affects CoNA versus CoCA. While there is some evidence that CoCA declines when the service sector share of labor is quite large, the transition of labor into services is strongly associated with reductions in CoNA throughout the transformation process.

Figure 12. Service sector development and the cost of nutrients (CoNA) or calories (CoCA)



Note: Data shown are residuals and semi-parametric estimates of the mean and its 95% confidence interval after controlling for GNI, GNI squared and fixed effects for each ICP region.

With this foundation, we extend our analysis to include more detailed dimensions of structural transformation by applying robust linear regression. Out of concern for potentially influential outliers in our data, we employ the *rreg* routine in Stata (version 15). We compare the effects of a given set of regressors on log CoNA, log CoCA, and the absolute difference between CoNA and CoCA. Our explanatory variables include:

- a quadratic function of GNI per capita

- service sector labor share
- urban population share
- average travel time to a city with population of 50,000 or more
- rural population share with access to electricity
- average duty on imports
- indicator variables for ICP regions.

Controlling for GNI helps to distinguish our hypothesized explanations for declining CoNA from other unobserved factors correlated with income. Including service sector labor share provides a further test of the results presented above and enables us to distinguish the effects of movement of labor from agriculture to services from the effect of rural to urban migration. Travel time to medium-sized cities is an indicator of the density of agricultural value chains. Access to electricity provides a broad indicator of the potential for cold chain formation, while average import duty provides a broad indicator of the effect of trade policy. Its impact on CoNA versus CoCA depends on the specific application of import duties to staple grains versus more nutrient-dense (and likely less tradable) dairy, animal sourced foods, and horticulture.

Structural transformation is an inherently circular process in which directions of causality are difficult to identify. Estimating these models from a single cross section precludes us from controlling for time-invariant country-level unobservables, while other data limitations inevitably result in excluded time-varying unobservables. We thus make no claim of causal identification. Rather we seek to establish plausible stylized facts consistent with our hypothesized explanations for the patterns we observe in the costs of nutritional and caloric adequacy.

Table 3 presents results for CoNA, in logarithmic form. We find that the quadratic (inverted-U) relationship between CoNA and national income shown earlier is generally robust to controls for each structural variable. The baseline specification in column 1 suggests that CoNA begins to fall when GNI per capita exceeds approximately $790. Against that background, we find additional links to the share of workers in the service sector and for rural transportation, as measured by the average rural resident's estimated travel time to a city with more than 50,000 people. Each doubling of the share of labor in services reduced CoNA by 0.5% beyond the effect of increased GNI. When considered without labor in services, urban population share is also associated with reductions in CoNA. Considered together, however, the former effect dominates. In addition, we find that denser value chains (indicated by shorter travel times to cities) also reduce CoNA. Doubling such travel times increases CoNA by 5%. Our results for rural population with access to electricity has the expected sign, but falls short of statistical significance. Similarly, the estimated effect of average import duties on CoNA is small and not statistically different from zero. With all regressors considered together, service sector labor share and value chain density emerge as the most robust explanations for reductions in CoNA.

Table 3. Structural transformation and the minimum cost of nutrient adequacy (dep var: lnCoNA)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
lnGNI	0.595**	0.562**	0.587**	0.610**	0.679**	0.726**	0.646**
	(0.277)	(0.263)	(0.271)	(0.273)	(0.305)	(0.317)	(0.305)
lnGNI squared	-0.042***	-0.036**	-0.039**	-0.043***	-0.045***	-0.048***	-0.040**
	(0.016)	(0.015)	(0.015)	(0.016)	(0.017)	(0.018)	(0.017)
Services share of labor force		-0.006***					-0.005**
		(0.002)					(0.002)
Urban share of population			-0.003**				-0.002
			(0.002)				(0.002)
Rural travel time to city >50k (log)				0.051**			0.040
				(0.025)			(0.024)
Rural electricity access (pop share)					-0.001		-0.000
					(0.001)		(0.001)
Import tariffs (ave. duty applied)						-0.002	-0.001
						(0.002)	(0.002)
Constant	-1.290	-1.149	-1.296	-1.558	-1.670	-1.775	-1.658
	(1.197)	(1.136)	(1.170)	(1.189)	(1.319)	(1.317)	(1.288)
N	134	134	134	134	134	134	134
R2	0.393	0.442	0.422	0.411	0.386	0.393	0.459
F	10.098	10.894	10.046	9.616	8.660	8.937	7.820

Note: Standard errors in parentheses, with significance levels denoted *** p<0.01, ** p<0.05, * p<0.1, from robust regressions (rreg). All specifications include indicator variables for ICP regions (not shown).

Table 4 repeats these specifications with log CoCA as the dependent variable. Here, too, the quadratic relationship with income is robust; however, the baseline specification suggests (in contrast to CoNA) that CoCA does not begin to decline with higher income until it exceeds nearly $3000. In further contrast to CoNA, CoCA is not associated with either the share of labor in services or the urban population share, but its link to value chain density (as indicated by travel time to cities) is both statistically significant and of greater magnitude than its association with CoNA – possibly a result of the substantially greater bulk and weight associated with the transport of staple grains as compared with horticultural output, for example. That rural electrification is associated with lower CoCA but not lower CoNA is contrary to our hypothesis, but consistent with an alternative view that electrification reduces transaction cost for bulk commodities even more than for nutrient-dense foods. That average import duty is more strongly associated with CoCA than CoNA suggests that, controlling for income and ICP region, variation in trade restrictions plays a larger role in staple grain prices than nutrient-dense foods, perhaps because the perishability of the latter makes them less tradable and more sensitive to other factors.

Table 5 considers the absolute difference between CoNA and CoCA across these same specifications. Here the results appear less robust. Yet, Table 5 provides at least suggestive evidence in favor of our hypothesis that movement of labor into services and urbanization disproportionately benefits the marketing of more perishable and more nutrient-dense foods relative to staple grains.

Table 4. Structural transformation and the minimum cost of caloric adequacy (dep var: lnCoCA)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
lnGNI	1.207***	1.246***	1.233***	1.153***	1.422***	1.397***	1.415***
	(0.385)	(0.382)	(0.386)	(0.390)	(0.406)	(0.435)	(0.443)
lnGNI squared	-0.076***	-0.075***	-0.075***	-0.072***	-0.086***	-0.085***	-0.082***
	(0.022)	(0.022)	(0.022)	(0.022)	(0.023)	(0.024)	(0.025)
Services share of labor force		-0.004					-0.002
		(0.003)					(0.003)
Urban share of population			-0.002				-0.002
			(0.002)				(0.003)
Rural travel time to city >50k (log)				0.081**			0.067*
				(0.035)			(0.035)
Rural electricity access (pop share)					-0.003**		-0.002
					(0.002)		(0.002)
Import tariffs (ave. duty applied)						-0.003	0.000
						(0.003)	(0.003)
Constant	-5.267***	-5.446***	-5.421***	-5.474***	-6.067***	-5.905***	-6.507***
	(1.663)	(1.647)	(1.665)	(1.698)	(1.752)	(1.810)	(1.870)
N	134	134	134	134	134	134	134
R2	0.442	0.455	0.446	0.420	0.483	0.454	0.464
F	12.376	11.511	11.075	9.962	12.874	11.462	7.980

Note: Standard errors in parentheses, with significance levels denoted *** $p<0.01$, ** $p<0.05$, * $p<0.1$, from robust regressions (rreg). All specifications include indicator variables for ICP regions (not shown).

Table 5. Structural transformation and the premium for nutrient adequacy (dep var: CoNA - CoCA)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
lnGNI	0.326	0.271	0.369	0.337	0.190	0.348	0.260
	(0.396)	(0.386)	(0.386)	(0.398)	(0.431)	(0.455)	(0.448)
lnGNI squared	-0.029	-0.021	-0.027	-0.029	-0.022	-0.030	-0.020
	(0.023)	(0.022)	(0.022)	(0.023)	(0.024)	(0.025)	(0.025)
Services share of labor force		-0.007**					-0.005
		(0.003)					(0.003)
Urban share of population			-0.005**				-0.003
			(0.002)				(0.003)
Rural travel time to city >50k (log)				0.024			0.022
				(0.036)			(0.035)
Rural electricity access (pop share)					0.002		0.002
					(0.002)		(0.002)
Import tariffs (ave. duty applied)						-0.000	-0.002
						(0.003)	(0.003)
Constant	0.777	1.008	0.517	0.609	1.355	0.700	0.990
	(1.710)	(1.665)	(1.667)	(1.730)	(1.863)	(1.891)	(1.892)
N	134	134	134	134	134	134	134
R2	0.456	0.471	0.483	0.456	0.460	0.454	0.492
F	13.077	12.278	12.852	11.529	11.757	11.435	8.934

Note: Standard errors in parentheses, with significance levels denoted *** p<0.01, ** p<0.05, * p<0.1, from robust regressions (rreg). All specifications include indicator variables for ICP regions (not shown).

Conclusions

This paper uses ICP data on prices for a standardized list of 195 widely-consumed foods, combined with USDA data on the nutrient composition of these foods and IOM estimates of nutrient requirements for the median adult woman, to estimate the minimum cost of acquiring sufficient nutrients to maintain an active and healthy life in 164 countries around the world. We compare that cost of nutrient adequacy to the cost of caloric adequacy, meaning a subsistence diet providing sufficient energy for daily work. The resulting premium reflects the added cost of balancing intake of all essential nutrients, meeting not only their minimum estimated average requirements but also staying within upper limits and average macronutrient distribution ranges associated with long-term health. We then test for systematic patterns in the cost of nutrients across countries, focusing on how agricultural transformation might alter development paths to influence the relative cost of post-harvest food systems.

Our central finding is that, controlling for income and region-specific factors, agricultural transformation towards off-farm activities is associated with lower retail prices for nutrient-rich foods. Items such as milk and eggs or fruits and vegetables are often perishable and use specialized supply chains, revealing the important role of post-harvest food systems in the cost of nutritious diets. Results presented here address variation across countries in 2011 using a standardized global food list, pointing to opportunities for research on temporal and spatial variation as well as the role of additional foods that might fill nutrient gaps at low cost in particular settings. Future work using these results will compare least-cost diets to observed food consumption in each country, and compare the opportunity cost of nutrients in each country to its prevalence of nutrient deficiencies. The data and methods presented in this paper could also be used for a variety of other studies, such as simulating cost reductions from fortification or supplementation with specific nutrients.

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