The nutrition transition and agricultural transformation:
A Preston Curve approach

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ABSTRACT: The nutrition transition in diets and health is closely tied to other aspects of economic development, including agricultural transformation and urbanization as well as demographic change and epidemiological transition from infectious to non-communicable disease. Over time, dietary patterns typically shift from widespread inadequacy of many foods and nutrients, especially for children and mothers, into surplus energy intake and rising obesity with continued inadequacy of healthier foods. Diet-related diseases remain the largest single cause of premature death and disability in all regions. This paper combines food availability and dietary intake data from more than 100 countries over 30 years with a wide range of other evidence to characterize the nutrition transition and its association with changes in agricultural production and the food environment, asking how future dietary patterns might be steered towards healthier outcomes as national incomes grow.

KEY WORDS: Global health, international agriculture, obesity, malnutrition, urbanization

NOTES: All results presented here are transformations of country-level data, with no identifying information about individual human subjects; together with a qualitative component using key informant interviews the project was approved by the Tufts University Health Sciences Institutional Review Board on 12 June 2015. All data originate in the public domain as documented in the text.

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Introduction and motivation

This paper uses a variety of data to test whether new technologies and institutions have brought structural shifts in the historical relationship of economic development to diet-related disorders (the nutrition transition), food production and distribution (the agricultural transformation), and governments' agricultural price policies that alter the relative cost of food (the development paradox). To describe these relationships and test for structural shifts we use non-parametric regression of population-weighted survey data on national income per capita. This "Preston Curve" approach has been widely used in public health research (Bloom and Canning 2007), and allows us to detect shifts in many aspects of agriculture and nutrition.

The nutrition transition, a term coined in the early 1990s by Popkin (1993, 1994), refers to systematic changes in nutritional intake, body size and health associated with economic development. The term focuses particularly on rising rates of obesity and diet-related diseases which were increasingly observed since the 1980s, alongside the improvements in height and mortality which had occurred slowly over many decades in now-industrialized countries and then spread rapidly to lower-income countries as documented by Fogel (2004), Deaton (2007) and others.

The agricultural transformation is a much older term referring to systematic changes in farm production and food markets observed alongside economic development, as part of the larger process of structural transformation and industrialization (Johnston and Mellor 1961). The term focuses particularly on the rising role of markets, specialization and input use within agriculture, as well as changes in labor use and farm size with the rise of nonfarm employment and increased consumption of nonfood goods and services. Agricultural transformation had been observed to occur slowly in the 18th and 19th centuries, then spread more rapidly in the 20th century as documented for example by Hayami and Ruttan (1971).

In recent years, popular attention and academic research has shifted rapidly from agricultural change and agricultural transformation to the nutrition transition, as illustrated by Figure 1. This picture shows the relative frequency with which each two-word phrase appears in English-language publications each year, vividly demonstrating the rising interest in nutrition relative to agriculture. Discussion of "agricultural change" in general peaked in 1988 and declined rapidly after 1992, while the narrower topic of "agricultural transformation" remained relatively constant until it too declined after 2003. Meanwhile the term "nutrition transition" came into sudden use in the late 1990s, expanded past "agricultural transformation" in 2007, and equaled "agricultural change" in 2008.

Figure 1. Agricultural transition and nutrition transition: usage in English-language books, 1985-2008
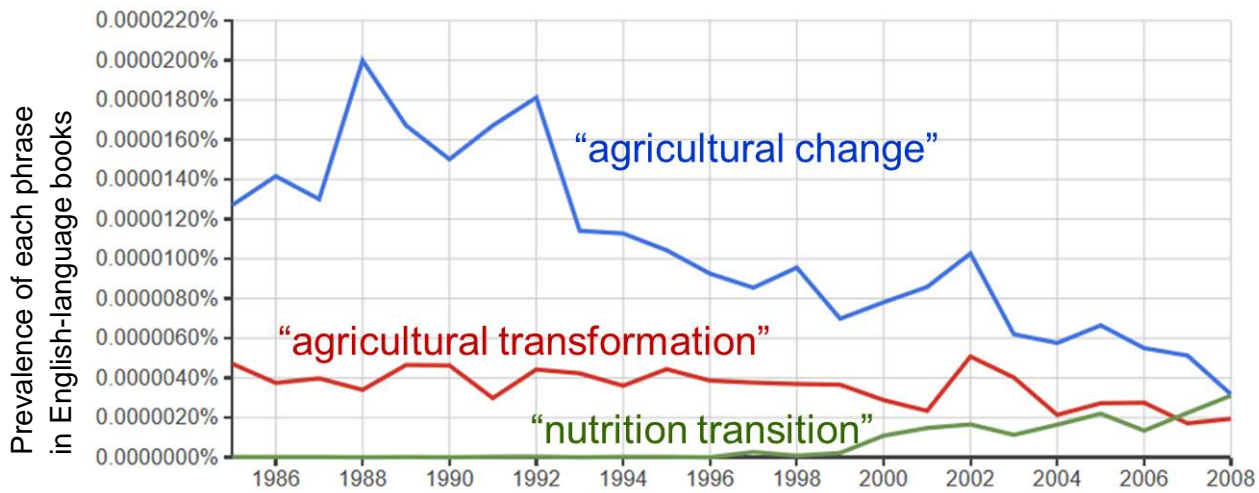
Source: Data show fractions of all two-word expressions in English-language publications digitized by Google Books, as computed on 24 July 2015 from books.google.com/ngrams/graph?content=agricultural+change, agricultural+transformation, nutrition+transition&case_insensitive=on&year_start=1985&year_end=2015&smoothing=0.

The switch illustrated in Figure 1, from a focus on agriculture (how to produce more food) to nutrition (which foods should be produced), reflects changes in the food supply itself as illustrated in Figure 2 below. That chart contrasts horizontal movements towards more food per person with vertical changes in diet composition in each region of the world. The length of each line shows the magnitude of change from 1961 to 2011, generally from left to right.

Figure 2. From more food to different foods: the dietary transition by region, 1961-2011
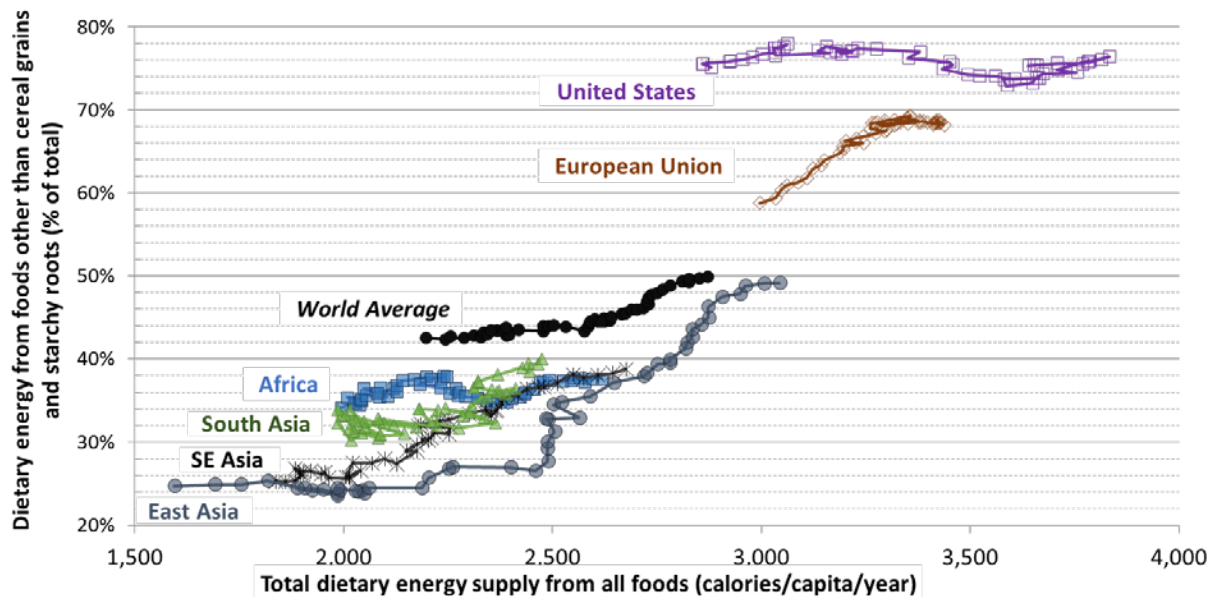
Source: Authors' calculations from FAO Food Balance Sheets, faostat3.fao.org/download/FB/FBS/E (June 2015).

Figure 2 shows annual estimates of total dietary energy per person on the horizontal axis and the share of that energy provided by non-staple foods, defined as products other than cereal grains or starchy roots. Neither variable is very precisely measured but presenting the data in this way reveals an elongated S-shaped pattern, by which the poorest countries (and the world average) first experienced a horizontal expansion of total food intake during the 1960s, which then turned up with an increasing share of foods from non-staple sources in the 1970s or 1980s, and then flattened again with horizontal changes seen in the US and recently in Europe where non-staples account for more than two-thirds of total energy intake. This chart reveals vividly the contrast between horizontal shifts at the bottom left and top right of the chart, and the diagonal movements in between. Those diagonal movements involve large changes in diet composition as well as food quantities. The chart also reveals variation in dietary diversity at both low and high levels of calories per person, with changes in dietary intake that are both cause and consequence of changes in health, body size and physical activity levels.

The nutrition transition and agricultural transformation illustrated above are closely linked to each other, both directly (to the extent that people in each country consume what their own farms produce) and indirectly (as agricultural change alters incomes and relative prices). Both are heavily influenced by government interventions, in ways that alter the path and may sometimes accelerate and sometimes slow the pace of change. In this paper, we review the empirical evidence on nutrition transition, defined as changes in diet-related disease burdens, body size and dietary intake, and the associated changes in agricultural employment and food price policies. Our aim is to compare national totals or averages for the largest possible number of countries around the world, asking whether the cross-country patterns observed so far in the 21st century differ from those seen when the nutrition transition was first described in the 1990s, perhaps because of structural changes in agriculture, food systems and other influences on diet and health.

To characterize the overall pattern of nutrition transition and agricultural transformation, we compare the population-weighted averages observed in each decade among countries around each level of national income per capita, measured in real terms controlling for the purchasing power of local currencies. This allows us to test for statistically significant changes in global patterns between the 1990s and the 2000s, generalizing the influential "Preston Curve" approach that was first applied to the relationship between life expectancy and per-capita income (Preston 1975, Bloom and Canning 2007). If the 21st century so far is like the 1990s, but with more of the same resources and greater purchasing power, then countries will have moved along each curve. If there has been a structural change of some kind, the curves themselves will have shifted.

The statistical technique used in this paper to estimate Preston Curves is a local polynomial regression, with confidence intervals to test the significance of differences in estimated means at each country's income level. Each observation is weighted by the country's population, so that the estimated means and confidence intervals represent all of the world's people living in countries at each level of per-capita national income. By definition, when successive observations move along a Preston curve they are following an established path associated with previous cross-country variation in per-capita income, while shifts in the curve represent a structural change in technology, demography, or social institutions. Estimating Preston curves with non-parametric regressions like ours allows the slope of that curve to vary with income, offering a simple and transparent test of whether the global pattern for each variable has changed over time.

The structural patterns we present relate malnutrition and agriculture to national income per capita, measured as GDP in purchasing-power terms. By design, GDP per capita is a very different concept than

household income. It is the sum of what all households, firms and public-sector institutions in a country produce and consume for each other, including public services such as infrastructure, education and health care. These services may shift individuals' own income-consumption curves and may affect everyone in a given country, so Preston curves do not necessarily reflect individuals' income elasticities and their Engel curves. This distinction may be especially important for agriculture, nutrition and health since outcomes in these sectors are highly responsive to public services, which are included in measured GDP but not counted in household income.

Another key feature of GDP of great importance for our Preston Curves is that it excludes the value of leisure time or work people do for each other within households. The only intra-household activity to be counted is on-farm consumption of crops and livestock, which is usually impossible to measure directly but is estimated each year by countries' statistical authorities. For the nutrition transition it is particularly important that GDP does not count family members' time spent on child care and home cooking, but it does count those same services if provided away from home by private firms, the public sector or philanthropic organizations. Movements along our nutritional Preston curves thus come from changes in the fraction of nutrition-related services provided from outside the household in the public or private sector, as well as changes in the absolute level of services provided. Those changes may improve or worsen nutritional outcomes.

Our Preston curves are estimated non-parametrically, so changes along the global development path may be S-shaped or U-shaped, and we allow that shape to change over time. In this way we test whether global changes, such as new kinds of international nutrition assistance programs or food markets, have altered outcomes for the average person at each level of per-capita income around the world. Before turning to the data, we first describe the previous literature on these transitions in more detail.

What is the nutrition transition?

The nutrition transition refers to a shift in dietary patterns from diets low in calories and nutrients, to diets high in calories but still inadequate in their balance of nutrients (Paarlberg, 2012). Excessive energy intake relative to energy expenditure, together with inadequate intake of some beneficial nutrients, is associated with consumption of more processed foods and more meals away from home. By the early 1990s, these dietary changes also began to occur in low- to middle-income countries and are now evident across Asia, Latin America, North Africa, the Middle East, and Sub-Saharan Africa (Popkin, 2001; Popkin et al. 2012).

Barry Popkin's influential work describes the nutrition transition as having three stages (Shetty, 2013): During the first stage, people consume a diet mainly of plant-based foods that is inadequate in calories. Many people produce their own food, which results in both a monotonous diet and a high level of mandatory physical activity. In the second stage, people gradually consume more calories overall, including more animal source foods, processed foods, fat, sugar, and other sweeteners. Fewer people produce their own food at home, so more food is purchased outside of the home and people perform less mandatory physical activity for food production. Finally, in the third stage, people transition to eating less fat, sugar, and processed foods and more whole grains, fruits, and vegetables. In addition, people perform physical activity voluntarily in their leisure time, but most people have not yet reached this third stage of the nutrition transition.

Clearly, the nutrition transition is closely linked to broader trends in economic, demographic, and epidemiologic conditions that alter dietary needs. At least some of the increased energy consumption observed in the second stage goes to maintain larger body sizes when people become taller, in addition to gains in weight relative to height. There are also large changes in physical activity both within and outside the home, as well as a decline in the prevalence of gastrointestinal and respiratory diseases which are closely linked to malnutrition (Schlaudecker et al., 2011). Large changes occur within rural areas and on the farm, compounded by urbanization (Nnyepi, Gwisai, Lekgoa, & Seru, 2015). The decline in macronutrient deficiencies is associated with declines in infectious disease but a rise in obesity and chronic diseases such as diabetes, hypertension, stroke, hyperlipidemia, cardiovascular disease, and cancer (Belahsen, 2014), and various conditions often coincide as a so-called double burden, triple burden, or more generally multiple burdens from many kinds of deprivation that call for a wide range of interventions (Webb, Luo and Gentilini, 2015). Throughout the nutrition transition, dietary risk factors remain among the largest contributors to the global burden of disease, giving agrifood systems the potential to significantly reduce illness associated with excess intake of harmful foods and insufficient intake of beneficial ones (Webb & Block, 2012; Imamura et al. 2015).

The nutrition transition and agricultural transformation

The dramatic rise in world food prices after 2005 brought renewed attention to the agricultural sector, and the influence of farming, farm inputs and post-harvest handling on both environmental conditions and diet quality. Agriculture's changing role is part of a larger structural transformation documented by Timmer (2002, 2009), as economic growth in other sectors raises their share of total output, employment, and expenditure, while rural-to-urban migration and productivity growth within agriculture allows farm incomes to catch up with nonfarm earnings (Norton, Alwang, & Masters, 2014). A long tradition of dual-sector models starting with Lewis (1954) identifies how agriculture provides food, labor and savings during urbanization and industrialization, fueling nonfarm growth and eventually also raising rural wages and ultimately eliminating the worst aspects of poverty.

During the agricultural transformation, total output per worker in agriculture typically remains well below the output of comparable workers in nonfarm activities (Gollin, Lagakos and Waugh 2014), fueling migration and resource flows to those other opportunities. The persistence of rural poverty is at least partly due to rural population growth, and hence declining availability of agricultural land, water, forests and other natural resources per agricultural worker. That decline in agricultural land per farmer persists until annual growth in nonfarm jobs exceeds growth in the total labor force, at which point the number of agricultural workers falls and the area of land available per farmer can increase (Masters et al., 2013). Throughout this process, farming remains dominated by self-employed family members, but in other respects the end result of this transformation is often convergence as agriculture grows increasingly similar to the other sectors of the economy (Timmer, 2009).

The gradual pull of resources out of low-income agriculture may lead it to be seen as a passive, lagging sector that is not responsive to government investment, but in fact the sector has been shown to offer high economic returns to public goods and services such as rural infrastructure, market institutions and agricultural technology. The sheer size of the sector in the early stages of economic development also makes agricultural productivity important for economywide growth, while the relative poverty of farmers makes agricultural productivity important for income distribution (Timmer & Akkus, 2008). Agriculture may be important for the time path of development as well, with targeted investments needed to overcome time lags in the linkages by which general economic development would otherwise benefit farm families in rural areas (Dorosh & Thurlow, 2014). For all these reasons, the pace of

agricultural development is very sensitive to the magnitude and quality of public investment in the sector, for improved technologies, institutions and infrastructure (Paarlberg, 2012).

Increasing agricultural productivity may be particularly important for improvements in nutrition, health and human capital, including the life prospects of rural children by raising their household income, nutrition and health status, life expectancy and earning potential (Webb & Block, 2012). Economic development and income growth, however, can bring unintended shifts in health and nutritional outcomes. Dietary patterns reflect increased consumption of processed foods, fats and oils, sugars and meat and dairy products, and disease patterns shift from infectious to chronic illness. These changes are seen to occur earlier in the process of economic transformation, with the burden of obesity shifting towards the poor (Popkin & Gordon-Larsen, 2004).

One potential cause of shifts in the pattern of agricultural transformation is more rapid natural increase within urban areas. During the 19th and early 20th centuries, urban areas had high mortality and low birth rates, requiring rapid in-migration from rural areas just to maintain the urban labor force. As urban sanitation and public health improved, cities increasingly replenished themselves with young workers who were themselves born in urban areas (Jedwab et al., 2014). This reduced migration opportunities for farmers' children, contributing to rural population growth. Urban development also influences those who remain in rural areas, of course: controlling for household income, farm children who live closer to older, larger towns are taller and heavier than those in more remote areas, and their mothers are more likely to be overweight (Darrouzet-Nardi & Masters, 2015).

The literature on agricultural transformation and nutrition transition reveals opportunities to anticipate structural changes in agriculture and nutrition, and design policies accordingly. Historically, government support for agriculture has increased as the sector shrinks and farm incomes rise, offering a puzzling "developmental paradox" (Barrett, 1999). The pattern is paradoxical because in poor countries a majority of the workforce is farming and is much poorer than those with nonfarm jobs, while in richer countries agriculture employs a small fraction of the workforce and offers earnings that are similar or higher than nonfarm jobs. Food price policy has thus redistributed income from poorer to richer and from larger to smaller groups, as documented most recently by Anderson (2009).

For dietary patterns, a principal concern is that government policies may have focused too much on starchy staples, missing opportunities to increase consumption of more nutrient-dense and healthier foods that could alleviate undernutrition while protecting against obesity (Pingali, 2015). In this paper we test for structural changes in food price policy influencing consumer prices for fruits and vegetables, relative to cereal grains or starchy roots. Prices paid by consumers have some influence on dietary choices, but many other variables also matter and can be influenced by public-sector intervention. The patterns revealed by our Preston curve approach reflect all kinds of public services, institutions and regulations that vary systematically with income and also shift over time. To identify the causal role of any particular policy choice would be far beyond the scope of this paper: our goal here is to exploit the vast increase in global data that has become available in recent years, and demonstrate the power of Preston curves to reveal past successes and potential dangers ahead.

Methods and data

In this paper, we characterize the global pattern of diet-related diseases, body sizes, food consumption, agricultural employment and agricultural price policies, and test for structural shifts between the cross-country patterns of the 1990s and of the 2000s in their relation to national income per capita. Our

approach generalizes the Preston Curve for life expectancy (Preston 1975, Bloom and Canning 2007), applying the same concept to nutrition and agriculture. In each case, we use the most widely available international source of data collected in a standardized way around the world. Each observation is a national total or average per person in that country and year. Some of these variables are modeled estimates, with interpolation and extrapolation where direct observations are not available. Others are more directly observed, using either the mean or a prevalence rate for the surveyed population.

Our project begins with careful attention to the available data sources. For our purposes, modeled estimates have the advantage of nearly universal coverage for all countries in each year, but the disadvantage that our statistical tests may in part be recovering the statistical methods and models used to create the data. In contrast, survey data are directly observed, but even when surveys are fully representative the choice of countries and years represented is vulnerable to selection bias. Some efforts, such as Demographic and Health Surveys (DHS), disproportionately occur in poor countries that have attracted foreign assistance to improve maternal and child health. Other kinds of data collection, such as dietary recall surveys funded by national governments, disproportionately occur in richer countries where governments are concerned about diet quality. We cannot control for this streetlight effect, but the method we use reveals which regions of the development spectrum are well represented in each kind of data, and offers some statistical control around the problem of missing values.

To explore patterns in the data using a consistent but flexible approach, we array all observations by the country's level of national income per capita, and scale each of the nationally-representative observations by the country's total population. This method for data visualization provides a clear picture for many kinds of variables. We then use nonparametric regression with a uniform bandwidth to provide consistent estimates of the population-weighted mean at each level of national income, with its associated 95 percent confidence interval to test for differences between the 1990s and the 2000s. That confidence interval is therefore wider for variables and in income ranges with few observations, or where the countries observed are small. Since India and China have exceptionally large populations and may not follow the same development path as smaller countries, we test their influence on all results.

The statistical method we use to estimate our Preston curves is a local polynominal regression with confidence intervals, implemented as command -lpolyci- in Stata 14. Since our independent variable is the same in each regression, we impose a consistent bandwidth so the pattern of estimated means can be compared among the dependent variables, and the confidence intervals allow hypothesis testing by direct visual inspection.

National income
The principal independent variable in our tests is national income per capita from the Penn World Tables, specifically PWT 8.1 released in April 2015. The specific variable we use is the value of each country's real domestic product per capita, computed using chained price indexes weighted by consumer expenditures to maintain purchasing power parity over time and across countries. This variable is known as RGDPEPC, to reflect Real GDP with Expenditure-side prices, Per Capita. Its calculation rests on a combination of national accounts and price surveys, offering the most authoritative source of data to compare relative living standards across countries and over time as described in Feenstra, Inklaar and Timmer (2015).

Food consumption
We begin our analysis with each country's total food consumption per capita from FAO Food Balance Sheet (FBS) data. These FBS data estimate consumption based on national governments' official

statistics for each food's total production minus exports plus imports, minus the FAO's own estimates for non-food uses such as seed, feed and losses up to the point of retail sale or retention by farm households. Food balance sheets are computed for all major food commodities, measured in terms of product weight (kg/cap/year) and then converted into dietary energy (kcal/cap/year) as well as protein and fat (g/cap/year) using food composition tables for the energy and macronutrient content of each commodity. The resulting total or per-capita average is often described as food supply, availability, or disappearance, and it differs from dietary intake by the amount of each food that is purchased but not eaten due to spoilage, kitchen waste, or plate waste. Details on FBS methods relative to dietary surveys are at FAO (2015) and Del Gobbo et al. (2015). In this paper, we start with FBS data on total food consumption followed by anthropometric evidence about average heights and weights, before turning to intake of specific foods and diet-related diseases.

Body size

To examine anthropometric changes in weights and heights over time, we begin with modeled estimates of adult obesity for all countries of the world as computed by the Global Burden of Disease (GBD) study. Then, for infants and children we turn first to the Demographic and Health Surveys (DHS) which are available in the public domain at http://www.dhsprogram.com/Data. The DHS are large, nationally representative household surveys funded primarily by the United States Agency for International Development (USAID) that provide comparable data for 75 countries between 1986 and 2014. The variables we use are mean z scores of height-for-age (HAZ) and weight-for-height (WHZ), measuring how all infants' sizes vary from the growth standards estimated by the World Health Organizations (WHO) for a reference population raised under the healthiest of circumstances around the world. Here we show data for all children under 5, recognizing that height data at the youngest ages (especially under 2) offers the most sensitive measure of recent deprivation among the surveyed population. Relatively large surveys are needed to achieve sufficient coverage, and measurement is relatively costly. For a given survey, the prevalence of stunting and wasting is more vulnerable to measurement error than the median or mean value (Bhagowalia, Chen and Masters 2011), so for that we use the even larger sample of observations in the World Bank-WHO-UNICEF joint Global Database on Child Growth and Malnutrition, for 146 countries between 1983 and 2015.

Diet-related disease

To compare the health damage caused by various diet-related diseases, we turn to the Global Burden of Disease (GBD) database which has been available for public download since 2014 at www.healthdata.org/gbd/data. The variables we use are shares of each population's lost disability-adjusted life years (DALYs) attributed by epidemiological modeling to various specific causes, for which the methods and main results were reported in Murray et al. (2012). In particular we consider the GBD study's estimated share of DALYs lost due to protein-energy malnutrition, iron-deficiency anemia and diarrheal disease representing one end of the nutrition transition, and the share lost due to diabetes, hypertension and ischemic heart disease on the other. The GBD used a variety of observations and assumptions to estimate values for 1990, 2005 and 2010, allowing us to test empirically whether the relative burdens of these diseases actually does vary with national income in the 2000s as it did in 1990, in the 162 countries for which we have both GDB and PWT data.

Dietary intake

Food consumption is difficult to measure directly, in part because it is so widely dispersed in space and time, and varies widely from day to day and person to person. Recall is problematic, and each kind of food may be described and measured in many different ways. For this study, we exploit the underlying data assembled for the GBD study by its Nutrition and Chronic Diseases Expert Group (NutriCoDE). They

compiled a total of 74 dietary recall surveys measuring intake of specific foods in comparable ways across numerous countries in various years from 1981 through 2009. A key feature of the NutriCoDE study was the use of nutritional epidemiology models to extrapolate from the dietary surveys to estimate food intake for all GBD countries. Here we show the NutriCoDE data for sugar-sweetened beverages and then a summary version of all GBD dietary risk factors, in the form of two diet-quality indexes. Both are scaled from 0 to 100, with larger numbers for healthier diets posing less risk of diet-related disease: one is based on more intake of relatively healthy foods, and the other is based on less intake of relatively unhealthy foods, as described by Imamura et al. (2014).

Agricultural transformation
The agricultural sector changes in many different ways; here we focus on year-to-year changes in rural population, and the agricultural sector's size relative to other activities in terms of total employment and production per worker. These are among the most visible and measureable features of agricultural transformation, capturing the degree to which demographic changes and resource flows equalize differences in life prospects between farm and nonfarm work.   For rural population growth we use the UN Population Projections released in 2013, and for employment by sector we use ILO (2015) estimates, combined with national accounts data on agricultural value added per worker from the World Bank. This provides a consistent framework for characterizing the agricultural transformation in terms of labor shares, income shares and output per worker, following Gollin, Lagakos and Waugh (2014).

Food price policy
Governments intervene to affect food consumption in a wide variety of ways. Here we focus on the most directly measurable, internationally comparable form of intervention, which is food policies that alter the prices paid by consumers. By convention, these are measured relative to the hypothetical benchmark of the prices one would observe with unrestricted international trade and the lowest attainable costs for transportation, processing and marketing. Actual prices paid by consumers may be higher, especially for imported goods where international trade is restricted, or lower as with exported goods where trade is restricted. The World Bank's Distortions to Agricultural Incentives project provides estimates of such price effects for all major food products for 85 countries from 1950 to 2011, from which we draw data for 1990, 2000 and 2010. The data and methodology behind these estimates is available at Anderson and Nelgen (2013).

Principal Results

The Preston Curve estimates in this paper reveal remarkable features of the nutrition transition, agricultural transformation and associated government policy choices, with clear differences in the income gradients for many variables. Without natural experiments generating quasi-random variation we cannot test for causal effects, but we can establish patterns and stylized facts to be explained and taken into account when predicting change over time or recommending new policies, programs and projects. Due to the large volume of data presented in this paper we limit discussion of each particular result, leaving detailed descriptions and further analysis to other work.

Food balance sheet estimates of consumption

FAO data using official government estimates of production, trade and other uses indicate that total consumption of dietary energy has a steep income gradient. As shown by Del Gobbo et al. (2015) these data are not always consistent with diet recall surveys, but they are often the only available estimates and are widely used for many purposes. The regressions presented in Figure 3 reveal that estimated dietary energy consumption shifted up from 1990 to 2010 in the poorest countries with per capita incomes less than about $2,000 per year. There was no such shift for middle- and higher-income countries, so the income gradient flattened slightly. For comparability with other figures this chart shows the world outside of China and India, although including them would not alter results. The income gradient from under 2500 to about 3500 kcal/cap/year could be due to many changes associated with higher national incomes, including a rising fraction of taller adults, more overweight people, and perhaps also more kitchen or plate waste.

Figure 3. Total dietary energy has shifted up at low incomes

Note: Symbols are sized by population, with year shown as 1990=green circles (132 countries), 2005=red triangles (154 countries) and 2010=blue squares (155 countries). Lines show each year's local means and confidence intervals for each year estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.

Source: FAO Food Balance Sheets; GDP and population are from PWT 8.1.

For dietary diversity, the FAO Food Balance Sheet data shown in Figure 4 reveal that the proportion of calories consumed from non-staple foods has a steep income gradient, more than doubling from about 30 to above 60 percent as incomes rise. From 1990 to 2010 there was a small but significant shift down for countries between about $8,000 and $16,000 per year in per capita income, indicating less improvement in this measure of dietary diversity. China and India are again excluded from this regression, as China would otherwise be an influential outlier whose below-average level of dietary diversity in 1990 rose towards the world average for its income level in 2010; were China and India to be included, the slight flattening of the income gradient shown here would be even more pronounced, with world averages in 1990 significantly lower at low incomes (between $1,000 and $4,000 per year) while the income gradient for 2005 and 2010 remain similar to those shown here.

Figure 4. The share of energy from non-staples has shifted down at higher incomes

Note: Symbols are sized by population, with year shown as 1990=green circles (132 countries), 2005=red triangles (154 countries) and 2010=blue squares (155 countries). Lines show each year's local means and confidence intervals estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.

Source: FAO Food Balance Sheets; GDP and population are from PWT 8.1.
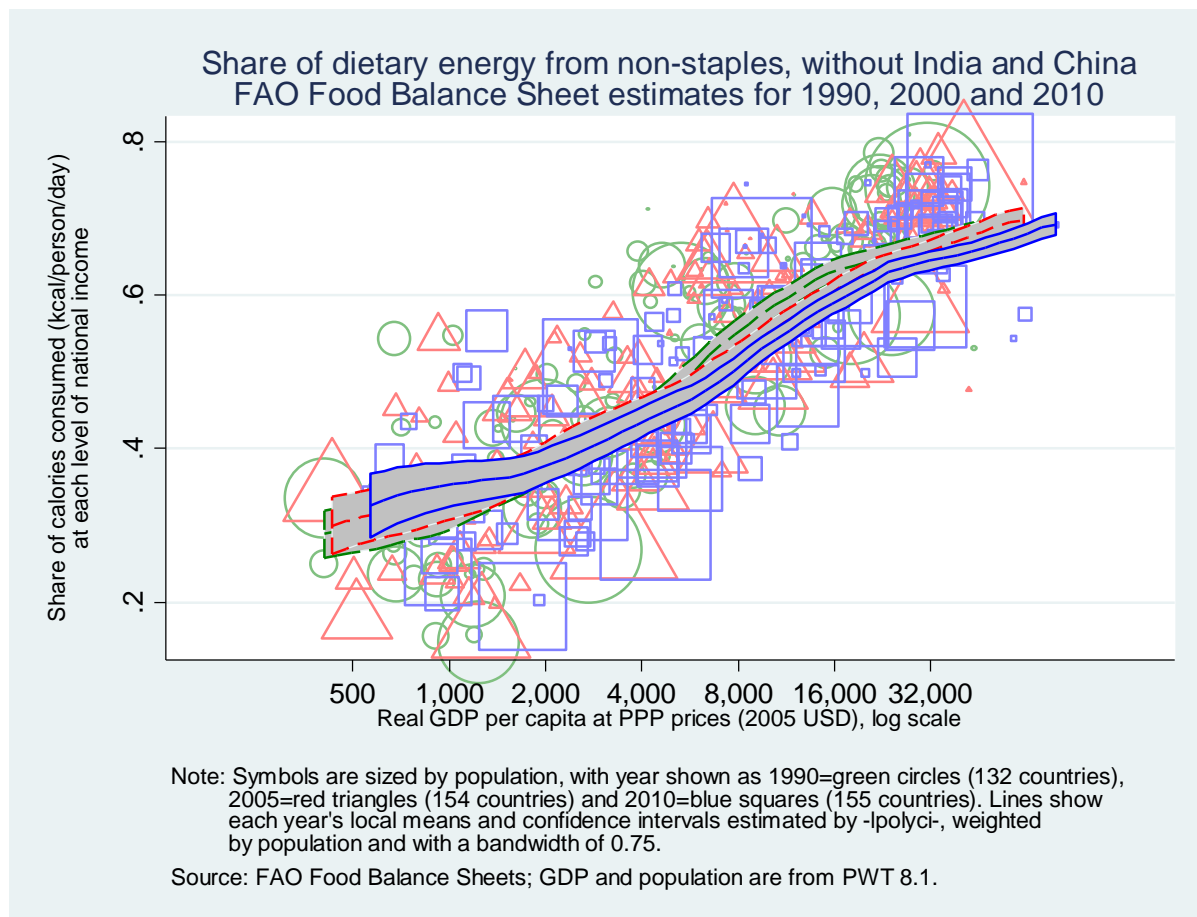
Body size for adults and children

As shown in Figure 5, the prevalence of obesity is significantly higher in the 2000s than in the 1990s in higher income countries (above $8,000 per person per year). Again, there is wide variation around the mean particularly at higher incomes. This figure excludes China and India, which are influential observations in the middle of this income range. When China and India are included, obesity prevalence is significantly higher in the 2000s only for the highest income countries.

Figure 5. The income gradient for adult obesity has shifted up at higher incomes

Note: Symbols are sized by population, with year shown as 1990=green circles, 2005=red triangles, and 2010=blue squares. Lines show each year's local means and confidence intervals estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.

Source: Global Burden of Disease Study; GDP and population are from PWT 8.1.
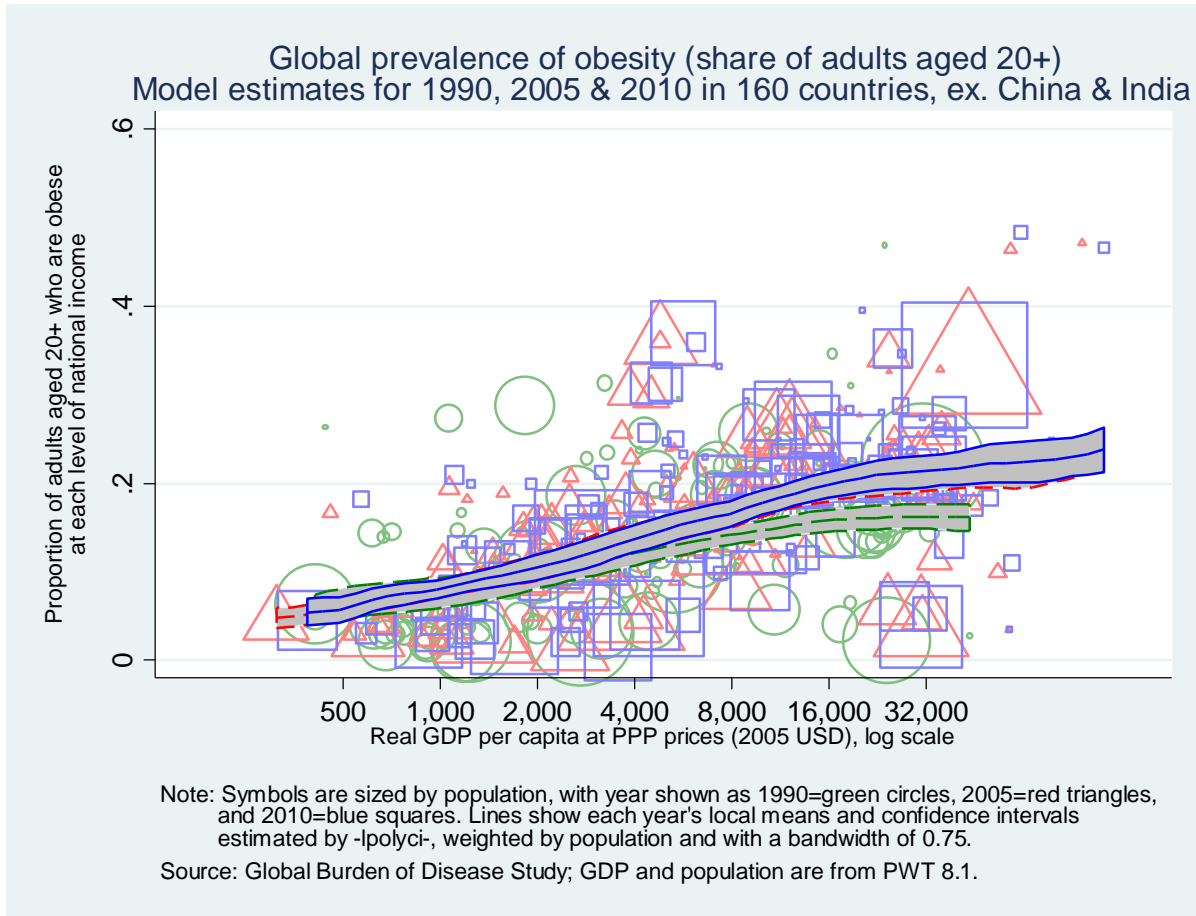
Using DHS data on mean standardized height-for-age as an anthropometric measure of child nutritional status, we find that the income gradient has remained steep in the 1990s and into the 2000s. Figure 6 shows only a non-significant upwards shift for the poorest countries. This chart omits India, which is an outlier with low heights for its income level in the 2000s. Were the India data to be included in this regression, the income gradient for the 2000s would be less steep, and significantly lower in the 2000s than in the 1986-99 at incomes greater than $4,000 per year.

Figure 6. The income gradient for child height is steep but has not shifted up

DHS survey data on heights of children under 5, excl. India
Population means in 1986-99 [n=61] and 2000-11 [n=101]

Note: Symbols are sized by population, with decades shown by green circles for 1986-99 (61 surveys in 41 countries) and blue squares for 2000-2011 (101 surveys in 51 countries). Lines show local means and confidence intervals for each period estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75. (Excl. India in 2006.)

Source: Demographic and Health Surveys (Statcompiler); GDP and population are from PWT 8.1.

The nutrition literature and global health policies often focus on the prevalence of stunting, defined as the proportion of children with a height-for-age z scores (HAZ) less than two standard deviations below the median of a healthy population. Changes in stunting are difficult to measure in part because they involve only the small fraction of children who move above or below that threshold from one survey to another, magnifying the effects of measurement error. To assemble the largest possible sample size we use the UNICEF/WHO/World Bank joint database, which reveals that stunting has fallen sharply at all national income levels from the 1990s to the 2000s. There remains a strong income gradient but also a major improvement at each level of income since 2000, as seen in Figure 7. This downward shift is a remarkable public health achievement, as new technologies and institutional arrangements lead to greater heights at each level of national income.

Figure 7. Child stunting rates have fallen sharply at all income levels

UNICEF/WHO/WB survey data on prevalence of child stunting
Pct. of children under 5, 1985-99 [n=250] and 2000-11 [n=337]

Note: Symbols are sized by population, with decades shown by green circles for 1986-99 (250 surveys in 103 countries) and blue squares for 2000-2011 (337 surveys in 117 countries). Lines show local means and confidence intervals for each period estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.
Source: World Bank, WHO and UNICEF joint data; GDP and population are from PWT 8.1.

Relative burden of specific diseases

The relative burden of selected illnesses is illustrated in Figures 8 and 9, expressed as their share of total DALYs lost at each level of national income. We start with diarrheal disease, which has long been the most important diet-related childhood illness in low-income countries. As shown in Figure 8, its burden has fallen sharply and is much lower in the 2000s than it was in the 1990s, especially in the poorest countries. A striking feature of these data is the wide variance among poor countries. Preston curves thus reveal not only the gradients associated with income growth and structural shifts over time, but also the variance in outcomes that might be attributable to other factors such as sanitation practices. In this case, we focus on variation among countries other than China and India, which would be influential observations. If included in such a regression, they would pull down the global mean for their income level in 1990, and raise it in 2005 and 2010, as they have experienced a less dramatic reduction in diarrheal disease burden than the other countries shown here.

Figure 8. Diarrheal disease burdens have fallen sharply for the poorest

Note: Symbols are sized by population, with year shown as 1990=green circles, 2005=red triangles, and 2010=blue squares. Lines show each year's local means and confidence intervals estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.

Source: Global Burden of Disease Study, Results by Cause; GDP and population are from PWT 8.1.
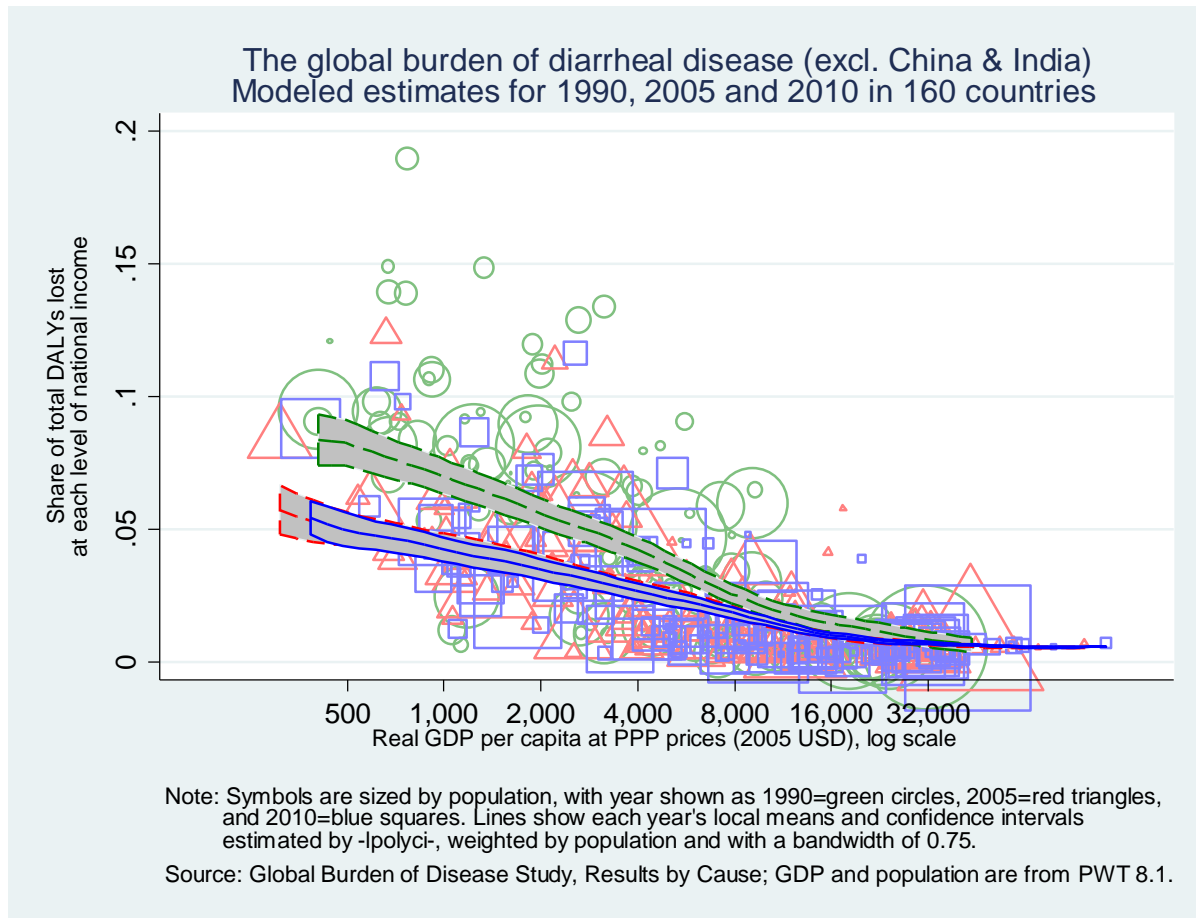
One of the most prominent diet-related diseases is diabetes, particularly for adults. Figure 9 establishes that its relative burden has shifted up significantly among low and middle-income countries. The shift upward in diabetes burdens at lower income levels is the opposite of the shifts shown earlier for obesity, which has an upward shift only at higher incomes. The relative burden of diabetes is rising in low- and middle-income countries in part because other diseases are being controlled there, while in richer countries obesity has risen without shifting up the associated disease burden in part due to successful diabetes detection and treatment. Similar concerns may apply to hypertension, cardiovascular disease and other non-communicable diseases whose relative burden is rising thanks to the control of infectious diseases such as diarrhea.

Figure 9. The relative burden of diabetes has risen most for the poor

Note: Symbols are sized by population, with year shown as 1990=green circles, 2005=red triangles, and 2010=blue squares. Lines show each year's local means and confidence intervals estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.

Source: Global Burden of Disease Study, Results by Cause; GDP and population are from PWT 8.1.
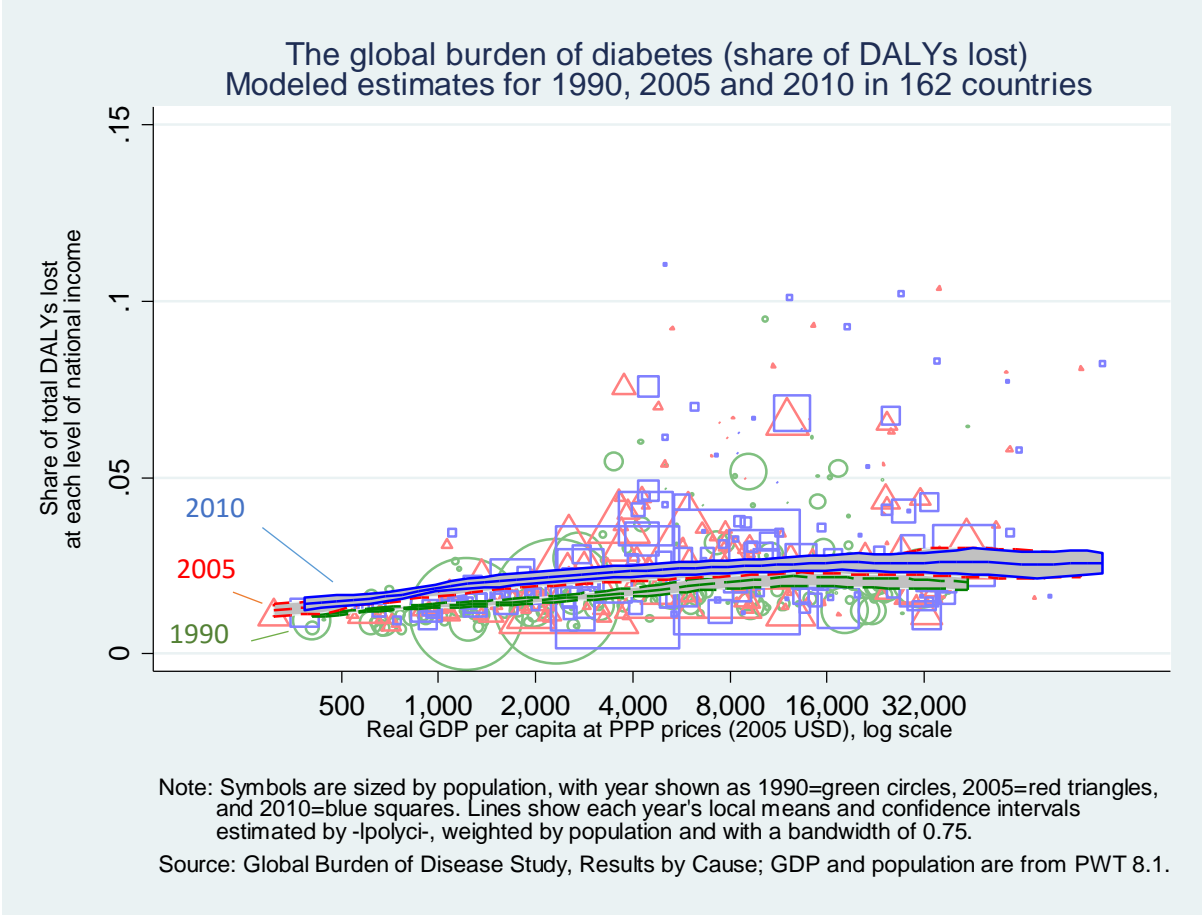
Dietary intake of specific foods

The FBS data shown above in Figures 2, 3 and 4 reveals large changes in per-capita consumption of major food commodities. In Figures 10, 11 and 12 we turn to dietary intake of specific foods and food components, using the dietary survey data collected by NutriCoDE in relation to health outcomes for the Global Burden of Disease project. Perhaps the most striking result from the GBD diet data is the shift in adults' sugar-sweetened beverage intake between decades. Prior to the year 2000, the few available estimates from dietary recall surveys indicated a gradual decline in sugar-sweetened beverage intake as national income per capita per year increased. In the first decade post 2000, intake estimates increase with income. Above $16,000 per person per year, sugar-sweetened beverage intake in the 1990s is significantly higher than in the previous decade, driven in part by a few large countries whose intake is far above the global mean. Since the number of countries surveyed is relatively small, however, the patterns seen in Figure 9 are vulnerable to sample selection bias as dietary surveys are more likely to include questions about sugar-sweetened beverages where policymakers are concerned about them.

Figure 10. Sugar-sweetened beverage intake has shifted up at higher incomes

GBD dietary data on adults' sugar-sweetened beverage intake
Population means from surveys in 1981-99 [n=58] and 2000-09 [n=47]

Note: Data shown exclude Australia in 1995, whose value is over 1,250 kcal/day.
Symbols are sized by population, with decades shown by green circles for 1984-99 and blue squares for 2000-2009. Lines show local means and confidence intervals estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.
Source: Global Burden of Disease Study; GDP and population are from PWT 8.1.
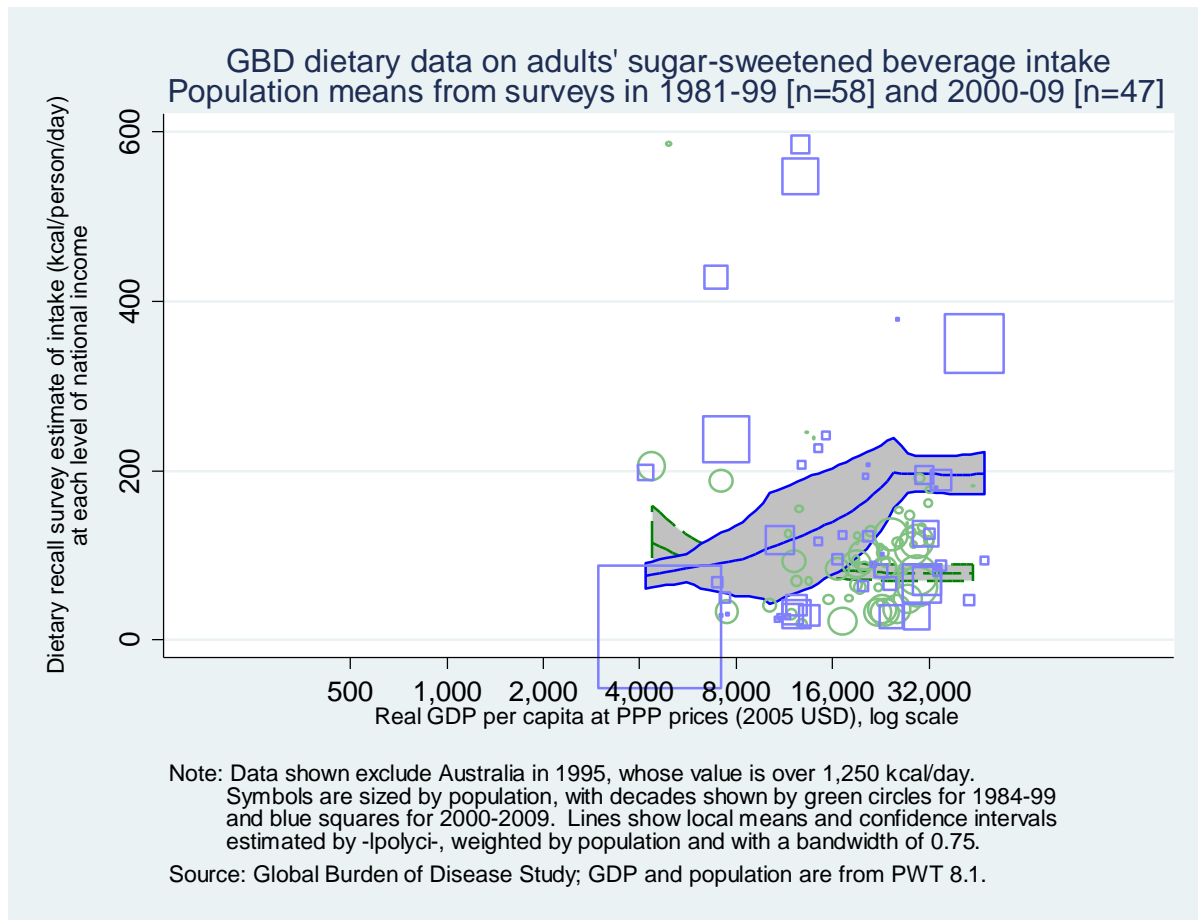
Figure 11 utilizes the dietary quality score based on intake of healthier foods from the NutriCoDE study. For the world outside of China and India, mean healthy-diet scores were significantly higher in 2010 than in 1990, but only in countries with per capita income greater than $16,000 per year. China and India are influential in this regression because they have lower-than-average scores in 2010. Were they to be included, the shift from 1990 to 2010 would no longer be statistically significant at any level of income.

Figure 11. Healthy food intake has shifted up at the highest income levels

Diet quality scores based on more intake of 10 healthier foods
(Model estimates for 1990 and 2010 in 161 countries, excl. China & India)

Note: Symbols are sized by population, with year shown as 1990=green circles, 2010=blue squares. Diet score is higher for more intake of 10 healthy items: fruits, vegetables, beans & legumes, nuts & seeds, whole grains, milk, polyunsaturated fatty acids, fish, plant omega-3s and fiber. Lines show means and CIs from -lpolyci-, weighted by population and with a bandwidth of 0.75.
Source: Nutrition and Chronic Diseases Expert Group (NutriCoDE); GDP and population from PWT 8.1.
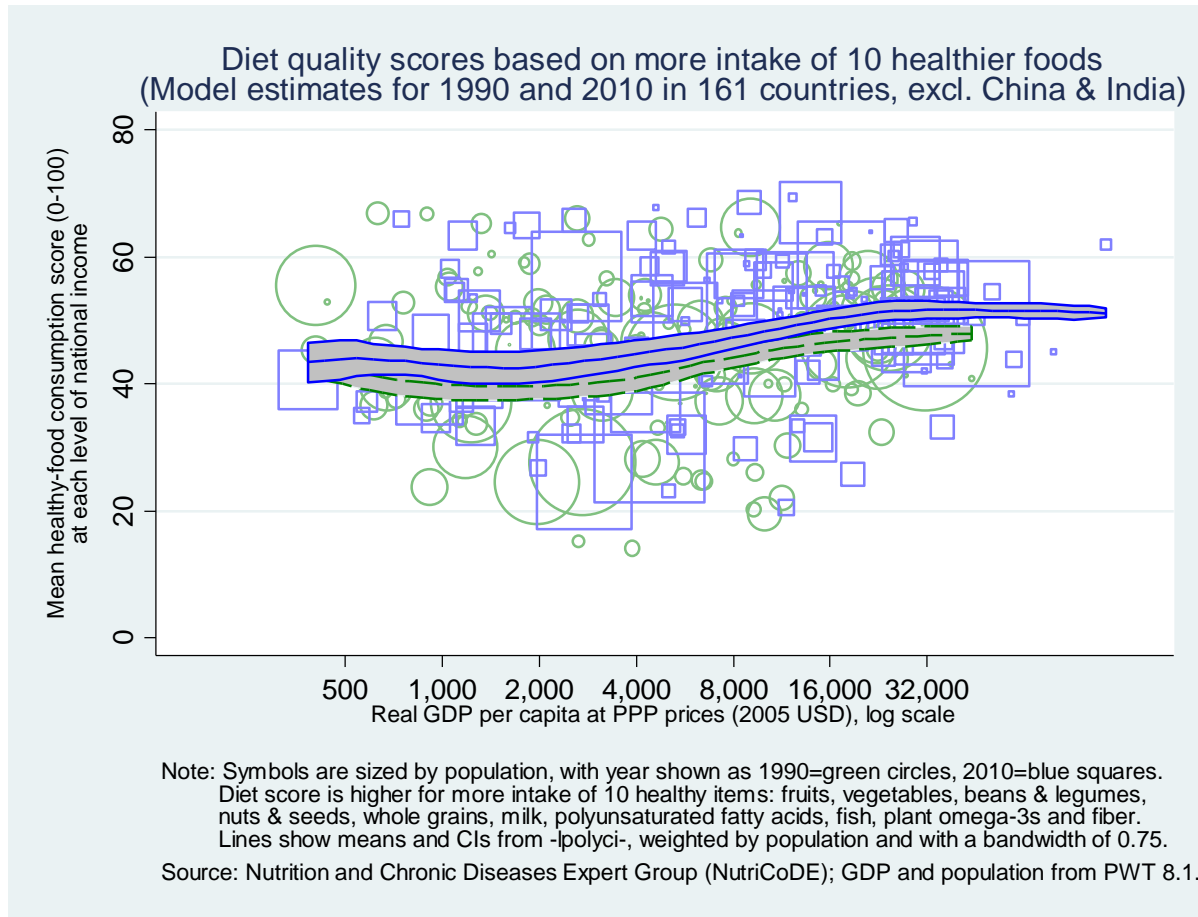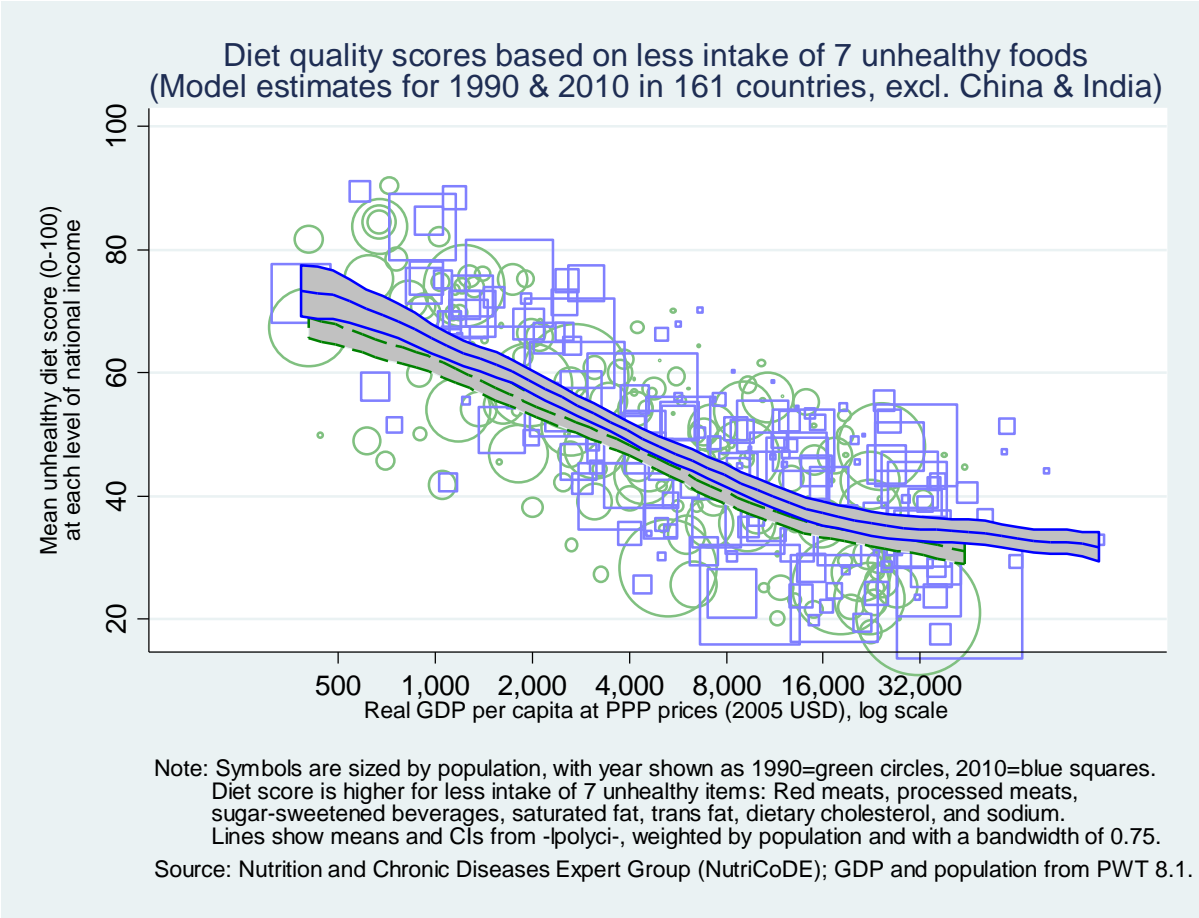
Figure 12 shows diet quality scores from the NutriCoDE study for average intake of *un*healthy foods, showing how this aspect of dietary quality declines with per capita income. Our Preston Curve approach reveals a strong income gradient but no significant shift from 1990 to 2010. Average diet quality at each level of national income is higher (less unhealthy) in 2010 compared to 1990, but the differences are not outside the confidence intervals. The comparison again excludes China and India, which had higher than average scores in 2010 as their incomes increased with relatively little increase in estimated consumption of unhealthy foods. Were these influential countries to be included, the upward shift would be statistically significant for countries above about $8,000 per year.

Figure 12. Unhealthy food intake has strong income gradient and has not shifted significantly

Diet quality scores based on less intake of 7 unhealthy foods
(Model estimates for 1990 & 2010 in 161 countries, excl. China & India)

Note: Symbols are sized by population, with year shown as 1990=green circles, 2010=blue squares.
Diet score is higher for less intake of 7 unhealthy items: Red meats, processed meats, sugar-sweetened beverages, saturated fat, trans fat, dietary cholesterol, and sodium.
Lines show means and CIs from -lpolyci-, weighted by population and with a bandwidth of 0.75.
Source: Nutrition and Chronic Diseases Expert Group (NutriCoDE); GDP and population from PWT 8.1.

Agricultural transformation

The nutrition transition described above is closely linked to agricultural transformation, as farm households gradually gain access to foods beyond what they can grow on their own land. The process of agricultural transformation is dominated by year-to-year variation in the number of people living in rural areas, which determines how much land, water, forests and other natural resources are available per rural person. An increase in the number of rural people implies a decline in those resources per person, giving them no choice but to farm with less land or in increasingly remote and unattractive areas; in the reverse case, when the number of rural people declines, each farm can have a larger footprint. Many factors influence the annual change in rural population, including the country's overall demographic transition and net migration rates out of rural areas. The year when rural population growth crosses zero has been called a "structural transformation turning point" (Tomich, Kilby and Johnston 1995), after which each remaining rural resident can expand their land use, contributing to higher rural incomes. Figure 13 shows rural population growth to have a steep income gradient in the poorest countries, from above 2 percent per year down towards the line of zero rural population growth which is reached at about $6,000 per year. At higher incomes, the direction of change over time is reversed, as rural population declines leave more land available per farm household. There is no significant shift in the gradient between decades in the world outside India and China. China has relatively large rural population declines in 2005 and 2010, so including it would show a significant downward shift at higher income levels after 1990.

Figure 13. Rural population increases rapidly in poorer countries, and declines in rich countries

Annual growth of the rural population, excluding outliers and India & China
Modeled estimates for 1990, 2000 and 2010 in 165 countries

Note: Symbols are sized by population, with year shown as 1991=green circles, 2000=red triangles, 2010=blue squares. Lines show means and confidence intervals for each year at each level of income, estimated by -lpolyci- with population weights and a bandwidth of 0.75. Excluded outliers are Afghan., Andorra & Falkland Is. in 1990, Andorra & W.Sah. in 2000, Japan in 2010.

Source: UN (2013) World Population Prospects; GDP and population from PWT 8.1.
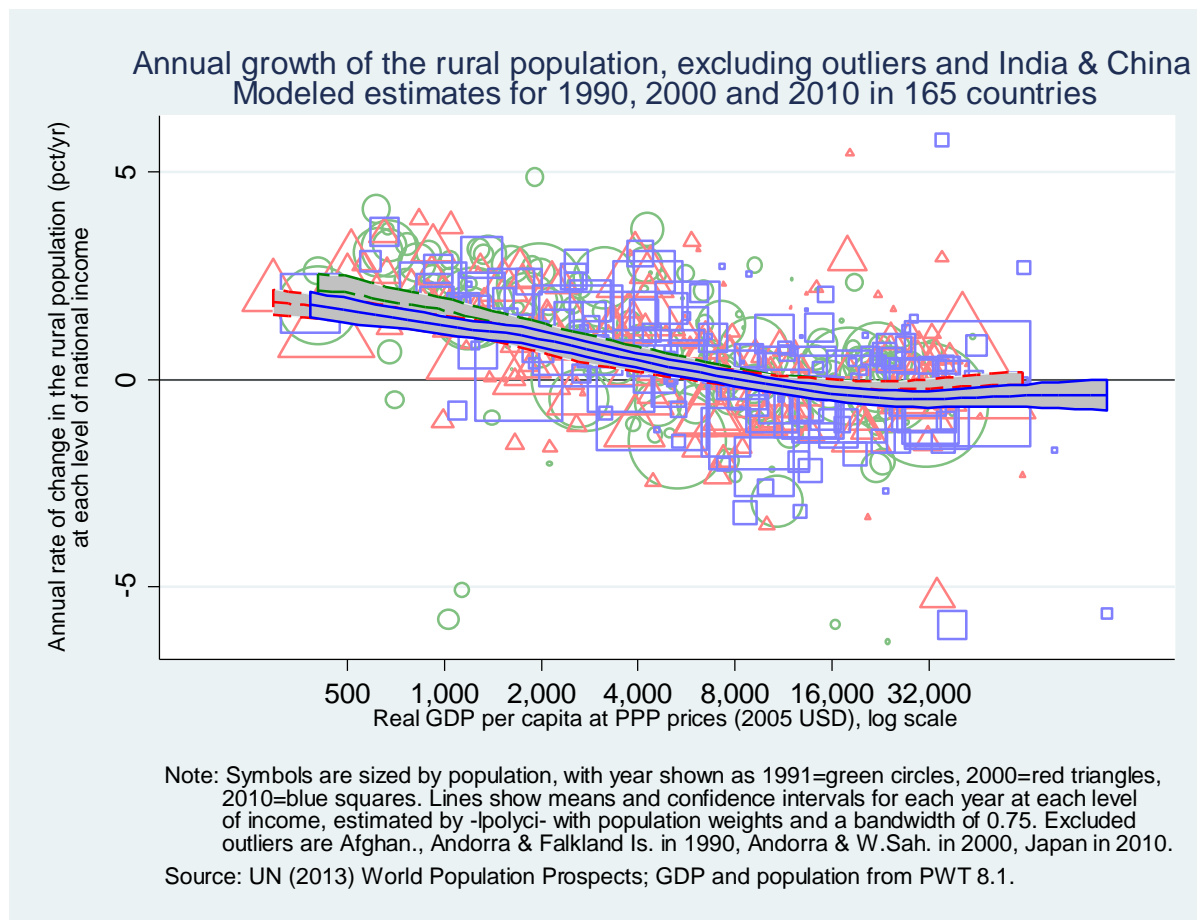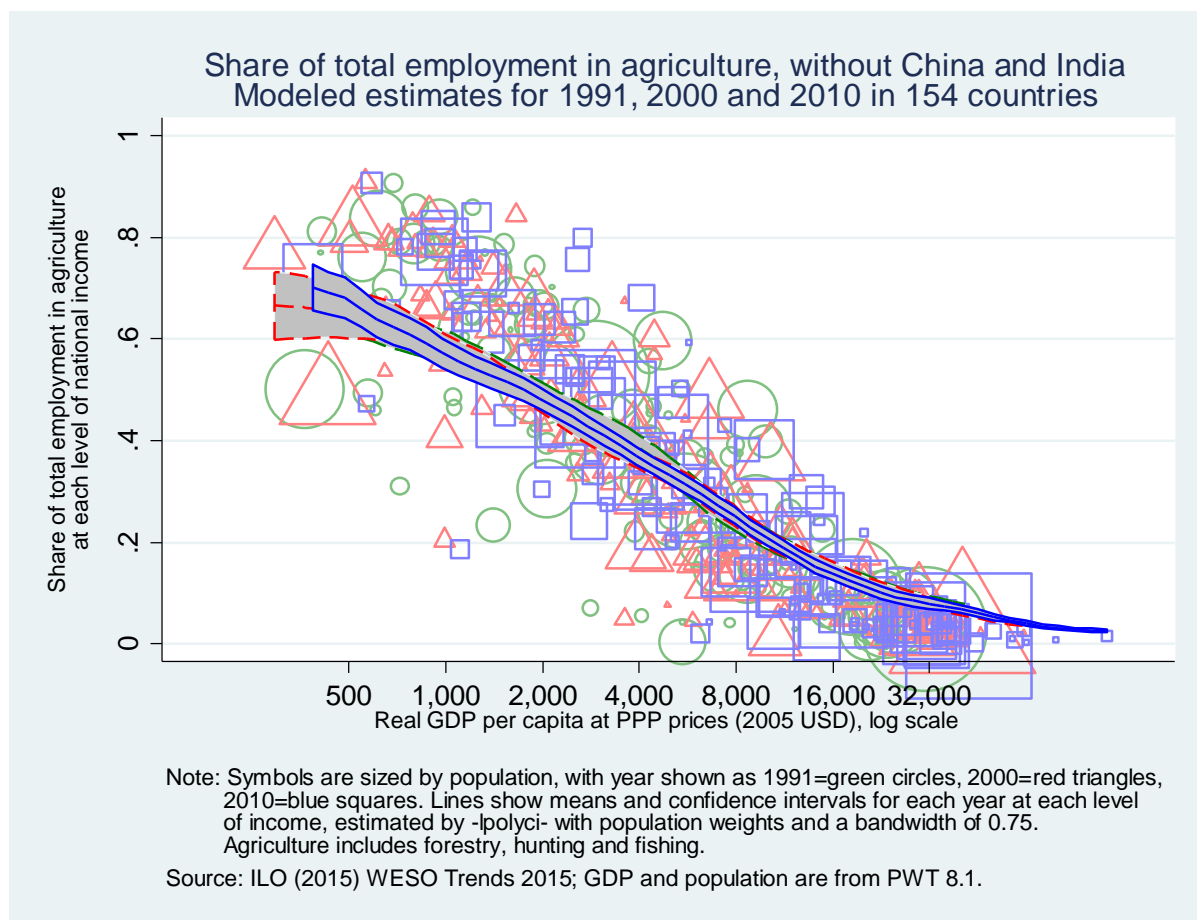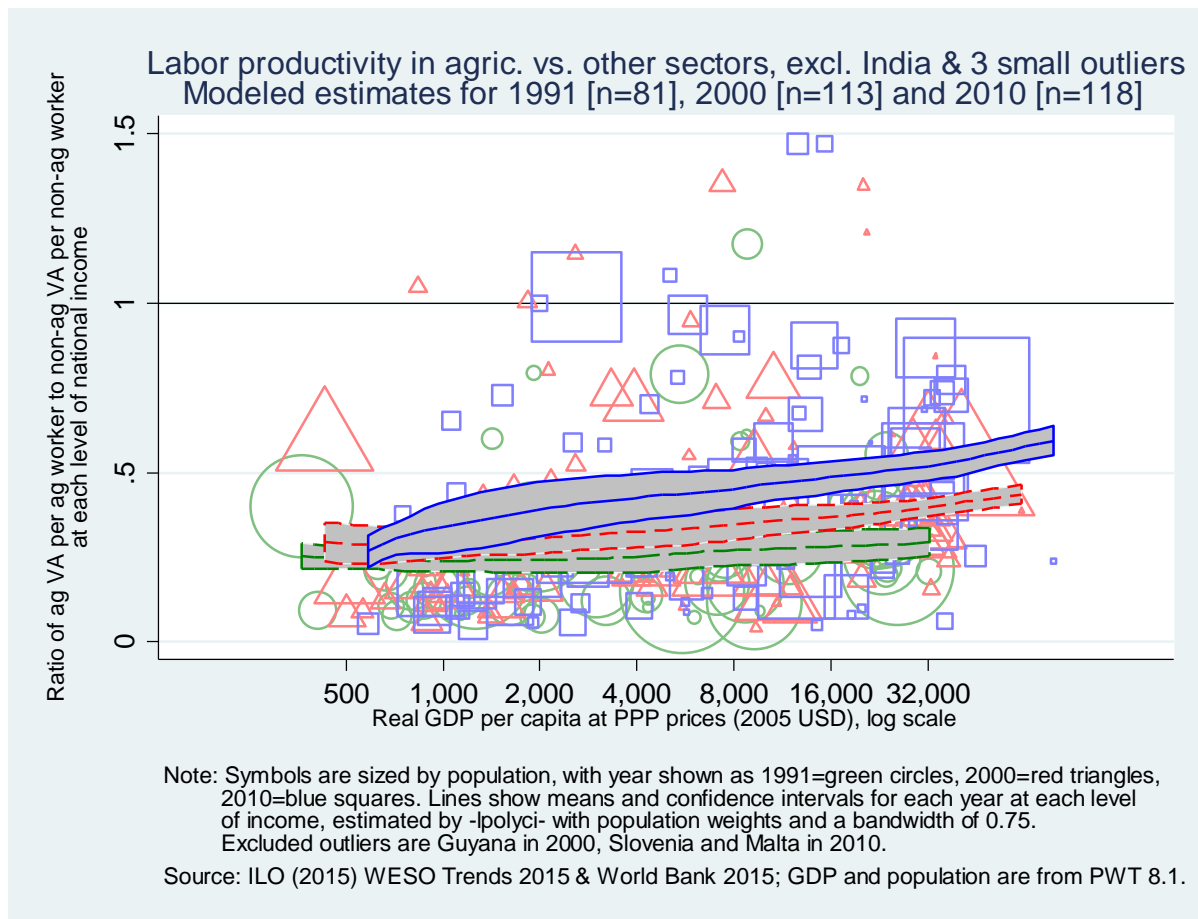
Figure 14 shows the steep income gradient in agriculture's share of total employment, as development brings resources into nonfarm services and industry. This ratio declines more than ten-fold, from above 70 percent in the poorest countries to under 5 percent in the richest, and there is no shift in that gradient over time. These data are of limited quality, however, as employment levels in agriculture are difficult to measure. The vast majority of workers in this sector are self-employed family members and many are also engaged in non-farm activities; labor allocation is especially hard to measure for women in agriculture as gender roles are complex and may be shifting rapidly over time (Doss 2014), so the stability shown in Figure 15 may simply reflect consistency in the ILO's estimation methods. The data shown here exclude China and India, which are influential outliers with exceptionally high agricultural employment shares for their income level.

Figure 14. Agriculture's share of employment falls steadily with income and has not shifted

Share of total employment in agriculture, without China and India
Modeled estimates for 1991, 2000 and 2010 in 154 countries

Note: Symbols are sized by population, with year shown as 1991=green circles, 2000=red triangles, 2010=blue squares. Lines show means and confidence intervals for each year at each level of income, estimated by -lpolyci- with population weights and a bandwidth of 0.75. Agriculture includes forestry, hunting and fishing.
Source: ILO (2015) WESO Trends 2015; GDP and population are from PWT 8.1.

Average earnings and productivity of farmers relative to workers in industry and services is illustrated in Figure 15. This chart is based on national accounts for each sector's total value added as reported by the World Bank, divided by each sector's total employment as estimated by the ILO. For visual clarity these charts exclude three countries with very high ratios in some years, but those outliers have small populations and little influence on the estimated means. China and India are also excluded. India has a low and influential level in 2010, which would keep the estimated means horizontal past India's income level of about $4,000 in that year. What Figure 16 reveals is that, for the world outside India, value added per agricultural worker had a significant upward shift at higher incomes in 2010 relative to previous years. In 1991 there was little income gradient, with average value added per farmer remaining at about 0.25 of value added per worker in nonfarm activities. In 2010 that ratio remained about the same in the poorest countries, but rose above 0.5 in the richest countries, with even higher levels in some cases. For example, the United States ratio was 0.5 in 2000 and 0.7 in 2010.

Figure 15. Output per worker in agriculture is lower than in other sectors, but has shifted up

Note: Symbols are sized by population, with year shown as 1991=green circles, 2000=red triangles, 2010=blue squares. Lines show means and confidence intervals for each year at each level of income, estimated by -lpolyci- with population weights and a bandwidth of 0.75. Excluded outliers are Guyana in 2000, Slovenia and Malta in 2010.

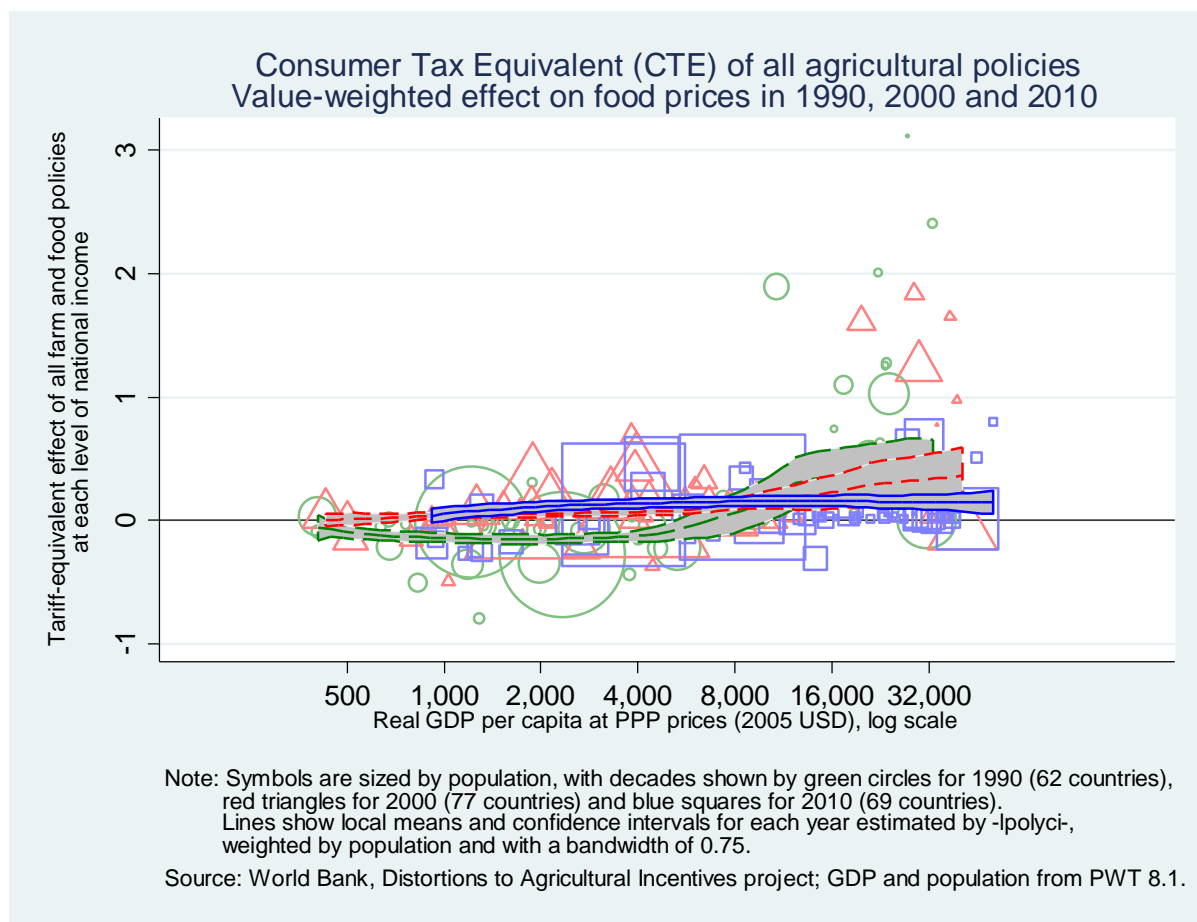Source: ILO (2015) WESO Trends 2015 & World Bank 2015; GDP and population are from PWT 8.1.

Food price policy

Governments in higher income countries have long been observed to raise prices for agricultural goods relative to other products and services, typically through more restrictive import policies and other measures, while governments in lower-income countries have typically worked to lower agricultural product prices, often by restricting exports (e.g. Anderson & Hayami, 1986). This longstanding pattern has been described as the "development paradox" in food policy (Barrett, Carter and Timmer, 2010).
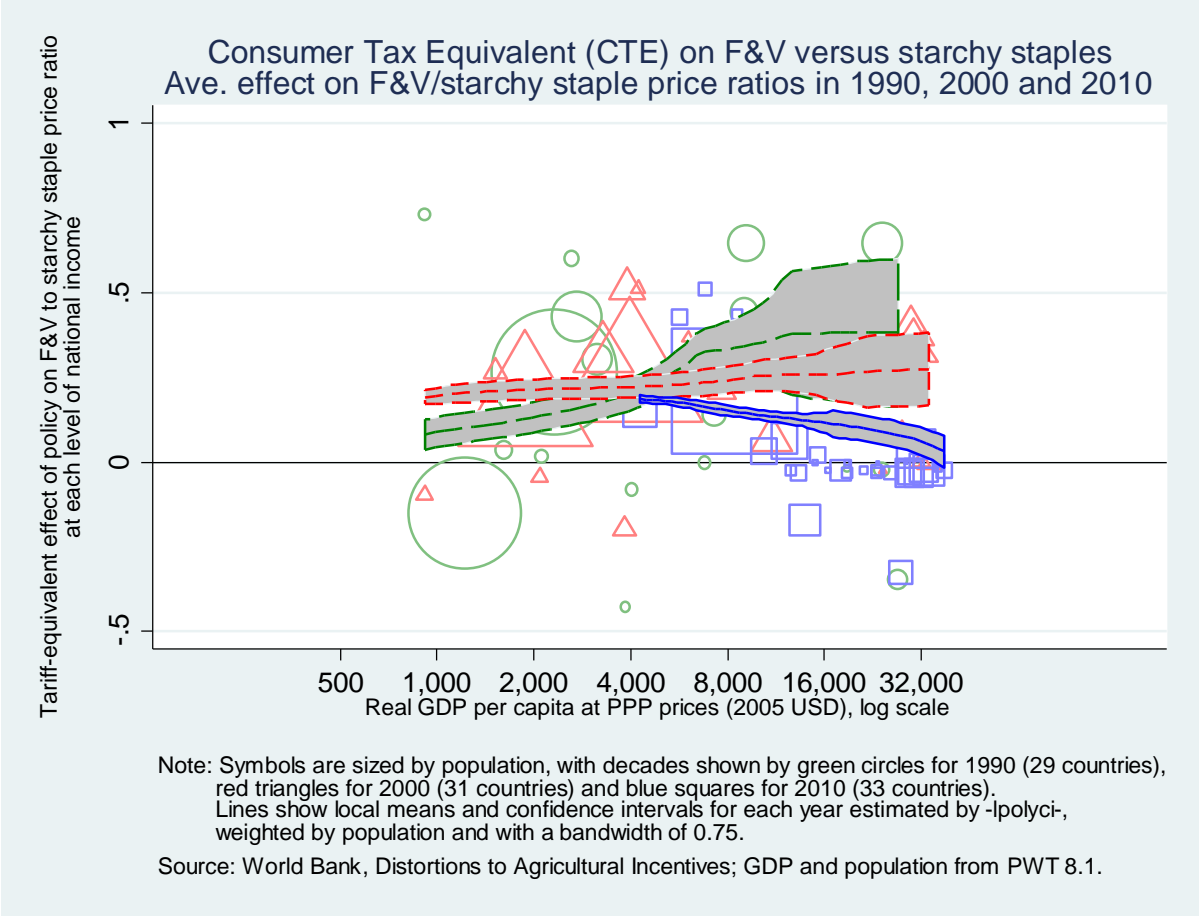
Figure 16 reveals that this paradox has largely disappeared, at least in terms of the prices paid by consumers for agricultural commodities tracked by the World Bank Distortions to Agricultural Incentives project. In 1990, governments of countries below about $4,000 per year acted to reduce agricultural product prices, shown here as a negative level of the consumer tax equivalent, with a strong income gradient towards raising prices in countries above about $10,000 per year. By 2000, governments in low-income countries were no longer lowering prices, and by 2010 governments in high-income countries were raising them much less than before, virtually eliminating the income gradient. These data include India and China, whose policies are close to the world averages for their income levels, so excluding them would have little influence on the results.

Figure 16. Food policy's "development paradox" is no longer

Note: Symbols are sized by population, with decades shown by green circles for 1990 (62 countries), red triangles for 2000 (77 countries) and blue squares for 2010 (69 countries). Lines show local means and confidence intervals for each year estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.

Source: World Bank, Distortions to Agricultural Incentives project; GDP and population from PWT 8.1.

The World Bank's estimates of agricultural price distortions can be used to measure government policy effects on relative prices among food commodities. Figure 17 shows the effect of policies on the average prices of all fruits and vegetables (FV) in a country, relative to policy effects on the averages prices of all starchy staples (SS) defined here as cereal grains and starchy roots. Policies for each kind of food are estimated as tariff-equivalent changes in the price paid by consumers, denoted t_{fv} and t_{ss}, and their combined effect on relative prices is the ratio of their effects $(1+t_{fv})/(1+t_{ss})$, minus one. This indicator would be zero if the two kinds of food are treated equally, but in most countries policies raise prices for F&V more than they raise prices for staples (or, in cases of export restrictions that lower prices, do so less for F&V than for staples). The index shown here is an unweighted average of all observations in the World Bank dataset, and many countries lack data for fruits and vegetables especially at lower income levels in the most recent year, but this "pro-staples" appears to have been significantly reduced in 2010, especially at higher income levels. The few observations we have for very low-income countries show an increase in the bias from 1990 to 2000 with no data available for 2010, while higher income countries show a decreasing bias over time, and a negative income gradient in 2010 as government policies in the highest-income countries raise F&V prices only slightly above prices for staple commodities.

Figure 17. Food policy's pro-staples bias is diminished

Note: Symbols are sized by population, with decades shown by green circles for 1990 (29 countries), red triangles for 2000 (31 countries) and blue squares for 2010 (33 countries). Lines show local means and confidence intervals for each year estimated by -lpolyci-, weighted by population and with a bandwidth of 0.75.

Source: World Bank, Distortions to Agricultural Incentives; GDP and population from PWT 8.1.

Conclusions

Preston curves reveal how observed outcomes relate to national per-capita income. The technique is purely descriptive, decomposing variance across countries and over time into three components: movements along a given curve that represent business-as-usual linkages between that outcome and higher levels of public and private spending, shifts in the curve that represent a structural change in how national income is spent, and variance around the curve that represents either measurement error or actual diversity in country circumstances at each level of income. In this paper we trace Preston curves for a wide range of variables in nutrition and agriculture, using population weights so that all means and confidence intervals are representative of all people in all countries for which data are available at each level of national income. This approach reveals both convergence along common growth paths and significant shifts in those paths from decade to decade, with important differences as well as similarities in changes for nutrition and agriculture.

Numerous limitations regarding data quality, including the question of which countries have data of any kind, are addressed in the text and detailed in notes on each figure presenting our results. At least some of the patterns and variation that we see are inevitably artifacts of measurement method and observational error. Future work will test the robustness of these results and also bring additional higher-quality observations, but what we have now is much more data, for more countries and time periods, than was available to researchers in earlier years. Future observations as more diverse societies reach high levels of national income will also be helpful to reveal the path ahead and potential endpoints as others gain access to more public services and greater purchasing power.

A first conclusion from the data available so far is that many of the Preston curve relationships are highly nonlinear. Our curves are estimated with respect to the logarithm of income, with the figures drawn with increments showing each successive doubling of income levels from world's poorest countries under $1,000 per capita to the world's richest above $32,000. In many cases we find sharply diminishing rates of change and several relationships become nearly horizontal in the wealthiest countries, suggesting an end point to that particular transition. When changes involve a transition from one level to another, simple extrapolation of recent trends is likely to be misleading, and Preston curves can help policymakers anticipate when changes are likely to accelerate or decelerate relative to national income growth.

A second conclusion is that shifts in the curves from decade to decade are typically significant only at certain levels of income, thereby altering the curves' shapes as well as levels. For example, from 1990 to 2010 the relative burden of diabetes shifted up in low- and middle-income countries, but not in places with national incomes above about $8,000 per year, while adult obesity rates shifted up significantly at the higher income level but not in poorer countries. This shift towards a steeper income gradient for obesity but a flatter one for diabetes reveals how detection and treatment has worked in richer countries to limit the progression of that disease, and will be increasingly needed in poorer places as their income growth puts more people at greater relative risk. Some of the most striking changes in global patterns are in agricultural transformation. For example, farmers' productivity relative to non-farm employment, in the sense of value added per worker, shifted up and acquired a much steeper income gradient over time from 1991 to 2000 and 2010. Agricultural policies also shifted greatly, including particularly a sharp decline in rich-countries policies that raised fruit and vegetable prices more than the prices of starchy staples. More favorable prices for fruits and vegetables could facilitate increased intake, with clear benefits for nutrition and health.

Our third and final observation concerns variation in and around the global averages, and what is to be learned from outliers or shifts over time in the global mean at each income level. Much more detailed studies of specific policies and programs would be needed to isolate potentially causal effects, but the Preston curves themselves reveal the magnitudes of what is at stake. One of the largest shifts is towards lower prevalence of child stunting at all income levels, made possible by a variety of changes leading to better health for at-risk children. Success in that domain suggests that similar improvements can be achieved elsewhere, bending the curves and breaking the patterns that were observed in the past. Many steps have already been taken, such as reducing the bias against fruit and vegetable consumption imposed by food price policies, but much remains to be done.

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