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Economic growth, convergence, and world food demand and supply

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ABSTRACT

In recent years, developing countries have been growing much more rapidly than the industrial countries. This growth convergence has potentially very important implications for world food demand and for world agriculture because of the increase in demand for agricultural resources as diets shift away from starchy staples and towards animal-based products and fruits and vegetables. Using a resource-based measure of food production and consumption that accounts for the much higher production costs associated with animal-based foods, this article finds per capita demand growth to be a more important driver of food demand than population growth between now and 2050. Using the middle-ground Shared Socioeconomic Pathway scenario to 2050 from the International Institute for Applied Systems Analysis, which assumes continued income convergence, the article finds that the increase in food demand (102 percent) would be about a third greater than under a hypothetical scenario of all countries growing at the same rate (78 percent). As convergence increases the growth of food supply by less than demand, it appears to be a driver of upward pressure on world food prices.

1. Introduction

The projected increase in world population from 7.4 billion in 2017 to 9.7 billion in 2050 (United Nations, 2019) has received a great deal of attention as an influence on world demand for food. However, as the rate of global population growth slows, growth in food consumption per person resulting from growth in per capita income is becoming an increasingly important driver of food demand. Engel's law points to a declining share of food in total expenditures as incomes grow, while Bennett's law points to an increase in spending on fruits and vegetables and animal-based products as incomes grow in developing countries (Godfray, 2011). The shift towards animal-based products puts pressure on agricultural resources since they require disproportionately more agricultural resources in production (Rask & Rask, 2011).

This relationship between food demand and income, summarized by Engel's and Bennett's laws, implies that income distribution matters for aggregate food demand (Cirera & Masset, 2010). Cirera and Masset (2010) also point out that—since most of global inequality is between rather than within countries—changes in the between-country income distribution are likely to have greater impacts on world food demand than changes in within-country distributions. Thus, in projecting long-run food demand changes, income convergence—where income per person has been growing more quickly in low- and middle-income countries than in high-income countries—has potentially important impacts on overall demand for food. This question of convergence, and its consequences for the distribution of income, has received considerable attention from macroeconomists, but its potential implications for food demand appear not to have been explicitly analyzed.

Neoclassical growth theory predicts that the differences in per capita incomes across countries converge over time, because the high-income countries at the technological frontier can grow only by adopting new technologies, while poor countries can potentially grow not only by adopting new technologies, but also by catching up with the leading economies in individual sectors (Abramovitz, 1986) and by shifting resources from low to high-productivity sectors (Gollin, Lagakos, & Waugh, 2013). However, the original literature on income convergence failed to find evidence of convergence between rich and poor countries, although it found convergence within 'clubs' such as today's rich countries (e.g. Baumol, 1986; Dowrick & Nguyen, 1989). In fact, Pritchett (1997) concluded that the dominant feature of economic growth since the 19th century had been 'income divergence, big time', with initially poorer countries growing much less rapidly than the more advanced countries.

More recently, however, there appears to have been a major improvement in the growth prospects of developing countries

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(Baldwin, 2016; Dervis, 2012). Dervis (2012) identified a 'new convergence' as having commenced around 1990, with more rapid growth in emerging and developing economies relative to advanced economies. Baldwin (2016) argues that a 'Great Convergence' is under way, with developed-country firms unbundling production stages and moving labor-intensive components of production to low-wage countries, allowing developing countries to industrialize without building entire supply chains from scratch. Bhalla (2017) points to the rapid expansion of educational opportunities in developing countries as a potentially complementary explanation. Many of the opportunities created by this convergence have been exploited by relatively large developing countries. Korotayev, Zinkina, Bogevolnov, and Malkov (2011) find strong evidence of unconditional convergence after 1998 among the 67 largest economies that accounted for 96 percent of world GDP and 86 percent of world population. The rate of convergence in future remains uncertain, with Barro (2015) pointing to strong convergence conditional on modernization, while Johnson and Papageorgiou (2020, p166) reject absolute convergence, fearing that the recent rapid growth of many developing countries may be a one-off effect of reforms.

Fig. 1 shows the extent of the turnaround from the era of divergence by comparing smoothed growth rates of per capita income for a group of developed countries defined by Rodrik (2011) with the per capita growth performance of the developing countries. It extends the Rodrik (2011) analysis of the Maddison data, updating using World Bank data to 2018. For almost the entire period between 1950 and 1993 per capita incomes grew more rapidly in the rich countries, with an average growth rate differential of 0.6 percentage points, substantially above the 0.3 percentage point differential that created Pritchett's 'big-time divergence' (1997, p13) between 1870 and 1960. Since 1994, however, the growth rate of developing countries has been higher by an average of 2.2 percentage points, and by an even more remarkable 2.7 percentage points since 2000.

Whether economic convergence has major implications for world food demand is an important question both for forecasting and for our ability to achieve the United Nations' Sustainable Development Goals (SDGs). Several of the 17 SDGs, including goals to end poverty and hunger, to promote inclusive economic growth and to reduce inequality within and between countries, pertain directly to the convergence and food demand question. For instance, if the world is successful in substantially raising the incomes of the poor during the time horizon of the SDGs (2015–2030) and beyond, what would be the impact on world food demand and supply? If populous middle-income countries continue to grow and upgrade their diets, will this put strong upward pressure on world food prices, potentially even threatening the access of some poor people to essential foods? This question was framed by Yotopoulos (1985) in the aftermath of the food price crisis of the 1970s, but it is not clear that we are much better placed to answer it now than when he posed it nearly forty years ago.

Substantial efforts have been made in the modeling community to forecast global supply and demand for food to the middle of the century, typically using large global agricultural models.[1] However, the projections for food output and prices vary widely across the models, depending on their underlying supply and demand specifications, choices of key parameters such as price and income elasticities and their treatments of technical change. For instance, reviewing modeling approaches from twelve global agricultural economic models, Hertel, Baldos, and van der Mensbrugghe (2016) report that modelers' projections for increases in global crop output between 2005 and 2050 range from 52 percent to 116 percent, while estimated changes in crop prices vary from a decline of 16 percent to a rise of 46 percent (Table 2, p. 429).

One way to disentangle the divergent results from modeling is to focus on a small number of key economic drivers that affect long-run crop output, price and land use changes. Pioneering work in this direction was undertaken by Hertel (2011) and Hertel and Baldos (2016) with the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE) model. This model relies on price responsive demand and supply of agricultural goods with extensive (area expansion) and intensive (yield growth) margins. Using the SIMPLE model, Hertel and Baldos (2016, p.30) find that long-run crop prices will most likely resume their downward trend between 2006 and 2050 but that these results are subject to a wide range of uncertainty.[2] They also conclude that income growth will be much more important relative to population growth than in the past.

While no other papers, to our knowledge, examine the impacts of economic convergence on food demand and supply, many studies in this area provide highly suggestive evidence on this issue. Surveying the literature on the relationship between income distribution and food demand, Cirera and Masset (2010) conclude that most existing models for projecting food demand fail to incorporate sufficient Engel flexibility, except for some models with flexible demand systems such as the Implicitly Directly Additive Demand System (AIDADS) (Rimmer & Powell, 1996). An important paper by Gouel and Guimbard (2018) overcomes this problem by using the highly flexible Modified Implicitly Directly Additive Demand System (MAIDADS) (Preckel, Cranfield, & Hertel, 2010). Their study projects increases in demand for animal-based calories between 74 percent and 114 percent, and for vegetable-based calories between 20 percent and 42 percent respectively towards 2050.

To assess the importance of economic convergence for world agriculture, we explore the evolution of world food demand and supply using simple econometric models originally developed by Fukase and Martin (2016) for an analysis of China's future food imports and self-sufficiency. We see this simple approach as a useful complement to structural models that specify consumer demand growth for different foods and then trace back through derived demand for animal feeds (see, for example, Anderson, Dimaranan, Hertel, & Martin, 1997; Hertel et al., 2016) because the complexity of such large-scale models means they rarely have the full flexibility needed to capture changes in demand and in intermediate input requirements, and frequently require ad hoc adjustments in order to generate plausible projections. In this paper, we model per capita consumption of aggregate food as a function of real income only, with a functional form developed to allow for consumption that asymptotically approaches a ceiling level (Rask & Rask, 2004, 2011). On the supply side, we specify aggregate food supply as a function of real income and agricultural land endowment per capita.

Following Yotopoulos (1985) and Rask and Rask (2004, 2011), we convert all food items into a resource-based measure of food, a cereal equivalent (CE)[3]. The key advantages of the CE demand and supply model (Fukase & Martin, 2016; Rask & Rask, 2011) are its parsimony and transparency. By shifting from calories delivered

[1] See Bodirsky et al. (2010), Hertel et al. (2016), and Valin et al. (2014) for reviews. See Nelson et al. (2014) and Wiebe et al. (2015) for the impacts of climate change on food yields and prices to 2050 under a range of socioeconomic and emission pathway scenarios.

[2] After specifying distributions for the underlying parameters and drivers of demand and supply, Hertel and Baldos (2016) undertake a Monte Carlo analysis and find a very broad range of potential outcomes for their global variables. They find that about 72 percent of the outcomes foreshadow a crop price decline while the remaining 28 percent correspond to price rises between 2006 and 2050 (Figure 11.7).

[3] The CE coefficients for livestock products reflect the feedstuff used to produce one unit of animal products in terms of the dietary energy equivalent of a unit of corn, considering not only grains consumed but also other types of feed such as protein supplements, forages (including pasture) and other feeds (Rask and Rask, 2011).

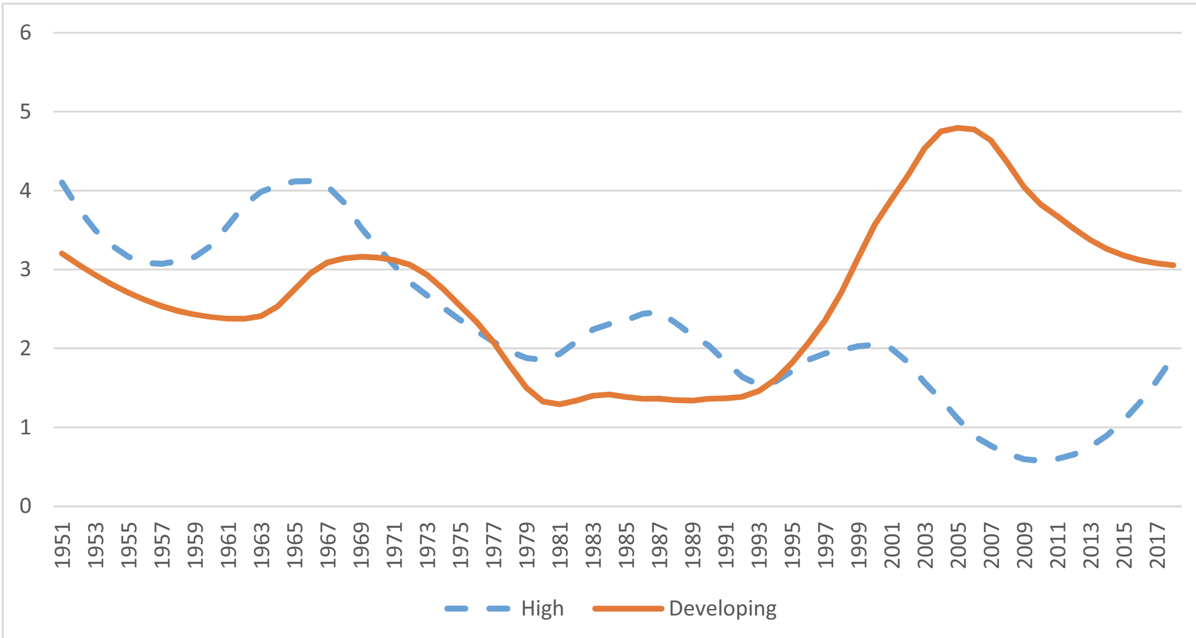

Fig. 1. Annual per capita GDP growth rates 1951–2018: Developed versus Developing countries, %. *Source*: Maddison (2010) data on GDP at 1990 PPP for 1950–2008 and World Bank (2019) data at 2011 PPP for 2009-2017. (Accessed 29 October 2019). *Notes*: Developed countries defined as in Rodrik (2011) as the US, Canada, Western Europe, New Zealand, Australia and Japan. Growth rates smoothed using the Lowess Regression model with span 0.33.

to the consumer, to the calories needed to produce the food, it accounts for the greater agricultural resource requirements associated with dietary upgrading, in particular, the large increase in resources required to produce animal-based products (e.g., cropland to produce feedstuff and pastures to graze animals). Contrary to previous studies using calorie-based measures of food consumption (e.g., Bodirsky et al., 2015; Gouel & Guimbard, 2018)[4], we find that per capita demand growth becomes more important than population growth in influencing food demand growth between 2009 and 2050. This trend contrasts with the historical pattern under which population growth dominated consumption per capita growth. It makes the relative importance of phenomena such as income convergence or divergence much greater than would have been the case in earlier decades.

Following this introduction, the next section examines the relationship between income growth, population growth and demand for food. The third section quantifies the extent of income convergence and its impact on food demand. The fourth section presents the relationship between economic growth, land availability and the supply of food. The fifth section considers the implications of income convergence for the supply-demand balance and for food prices towards 2050. The final section presents a brief conclusion.

2. Modeling food demand

We start this section by comparing our measures of cereal equivalents (CE) (Rask & Rask, 2004, 2011; Yotopoulos, 1985) with traditional measures based on calories delivered to the consumer. The CE measures convert foods into cereal equivalents based on the energy needed to produce them. The approach accounts for a central feature of food demand under income growth—the shift from reliance on direct consumption of grains and other starchy staples into more diversified diets including edible oils and protein-rich animal products. This dietary upgrading helps reduce problems such as stunting among children (Headey, Hirvonen, & Hoddinott, 2018), but imposes greater burdens on agricultural resources since production of more diversified, and particularly animal-based, diets requires much more agricultural output than plant-based diets (Fukase & Martin, 2016; Rask & Rask, 2011). For instance, the CE coefficient used to convert carcass beef into cereal equivalents was 19.8, reflecting the large amount of feed used directly to produce beef, the relatively low dressing weight percentage for live cattle, and the feed needed for breeding cows and heifers. Pork and poultry are more efficient as reflected in lower CE coefficients of 8.5 and 4.7 respectively, both because of generally higher feeding efficiencies and the lower costs of maintaining their breeding stocks. The magnitudes of the CE coefficients appear to be broadly consistent with estimates of relative land requirements in the literature (e.g., Gerbens-Leenes & Nonhebel, 2002 for the Netherlands; Zhen et al., 2010 for China). Gerbens-Leenes and Nonhebel (2002) estimate the land requirement for beef to be 20.9 m^2 year per kilogram of meat which is more than twice that for pork (8.9 m^2 year per kilogram of meat) and 15 times the requirement for cereals of 1.4 m^2 per kilogram per year.

Fig. 2a shows estimated global CE consumption curve along with the actual changes in CE consumption between the beginning of the period (1992) and the end (2009), for the World Bank's regions.[5] The CE consumption-income relationship is specified using the coefficient estimates in Fukase and Martin (Table 2, 2016), which

[4] Decomposing changes to caloric food demand into population and income effects between 2010 and 2050, Gouel and Guimbard (2018) find that total demand growth for food is more driven by population growth than by income growth. However, for the subset of animal-based products, the income effect appears to outweigh the population effect in influencing food demand growth (Table 5, p.398).

[5] Under the World Bank country classification, all countries above a certain threshold Gross National Income (GNI) are classified as 'high' income countries (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519). Only 'developing' countries are included in the 'regions', namely East Asia and the Pacific (EAP), Europe and Central Asia (ECA), South Asia (SA), Latin America and the Caribbean (LAC), Middle East and North Africa (MENA) and Sub-Saharan Africa (SSA). We classify countries into high and developing countries based on their 1992 income levels. This is because defining country groups at the end introduces systematic bias into growth rate comparisons by consistently subtracting better performers from the lower income group and adding better performers to the higher income group.

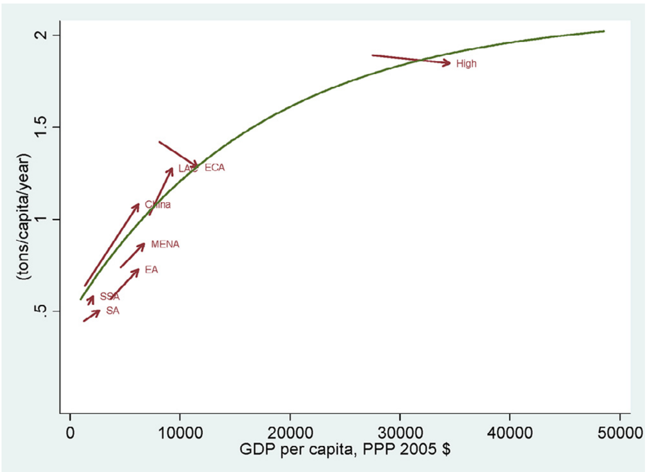

Fig. 2a. Changes in CE food consumption, 1992–2009. *Sources*: FAOSTAT and the World Development Indicators. *Notes*: The start and end points of the arrows are CE consumption for 1992 and 2009. The country labels are placed at the ending points.

extends the food demand analysis by Rask and Rask (2011) to 1980–2009.

$$y = 2.2 - 1.7 \cdot \exp\left(-5.8 * 10^{-5} \cdot x\right) \quad (1)$$

[0.16] [0.15] [1.1*10^{-5}] [6]

where y is CE consumption per capita and x is Purchasing Power Parity (PPP) Gross Domestic Product (GDP) per capita in 2005 constant prices. The estimated CE curve shows a concave relationship between CE food consumption and real income levels: with demand rising much more rapidly at low income levels when consumers are likely to spend a large proportion of increases in their incomes on food; CE consumption continues to increase as incomes grow, albeit at a slower rate, as consumers substitute foods with relatively high income elasticities (such as animal products) for cereals and tubers; and finally, CE consumption growth tapers off at higher levels of income (Rask & Rask, 2011). For most regions, the levels of per capita CE consumption and their growth between 1992 and 2009 are consistent with the estimated curve in the relevant income ranges. Two exceptions were the ECA region and the high-income countries as a group. In the ECA region, consumption of livestock products fell drastically following the move away from central planning, as the high cost of these products became evident (Rask & Rask, 2004). In exploratory work in Fukase and Martin (2016), we estimated Eq. (1) with a price distortion variable, but this reduced the sample by more than half without greatly changing the coefficients of interest.

In high-income countries, there has been a shift away from the most resource-intensive meats, such as beef, and towards more efficiently produced products such as poultry. In contrast, all non-ECA developing regions increased their consumption as their incomes grew. China's high economic growth saw a rapid increase in CE food consumption, with its per capita CE consumption increasing by about 70 percent over the period. China's ongoing dietary shift, which reflects increasingly affluent life-styles induced by high income growth, appears to have been a major driver behind this change (Fukase & Martin, 2016).[7] Fig. 2a reveals much lower levels of income and CE consumption for the South Asia (SA) and Sub-Saharan Africa (SSA) regions than others. The SA region, has the lowest per capita food consumption in cereal equivalents, perhaps partly reflecting the large fraction of people who are vegetarian in this region (Alexandratos & Bruinsma, 2012). Despite this, food demand in the region rose with income over the 1992 to 2009 period. In SSA, food demand was roughly as responsive to income growth as China, although the response was smaller because of the much smaller rise in income per person.

Turning to measures of calorie consumption, Fig. 2b shows the changes in food consumption between 1992 and 2009 by region with the global calorie consumption trend curve. The regional changes in calorie consumption are broadly in line with the global calorie trend line, revealing a concave relationship between income and food consumption albeit at a much lower level relative to the CE measure. The pattern of calorie consumption per person shown in Fig. 2b is broadly consistent with the patterns reported in the previous literature.[8]

Using Eq. (1), Fig. 2c shows the estimated demand for cereal equivalents and that for calories on a comparable scale (Fukase & Martin, 2016). The figure shows that consumption of calories levels off much earlier and at a much lower level of income than consumption of cereal equivalents. This is because the latter measure reflects the increasing agricultural resource requirement resulting from dietary shifts which continues after calorie consumption stabilizes.

2.1. Past and future growth in global food demand

In Table 1, we decompose total growth in global food demand into parts due to population growth and to per capita consumption growth. The first three columns of Table 1 report the evolution of CE food demand for our 134 sample countries, which account for 95 percent of 2009 population.[9] CE food demand grew annually at 2.3 percent in the 1980s, 2.1 percent in the 1990s and 1.9 percent in the first decade of the new millennium.

The next three columns in Table 1 decompose the change in CE food demand annual growth rate into per capita consumption growth and population growth. Table 1 reveals that the annual average growth in per capita food demand has become increasingly important, rising from 0.55 percent per year in the 1980s to 0.69 percent per year in the 1990s and 0.72 percent in the 2000s respectively while annual average population growths have decreased, from 1.75 percent in the 1980s to 1.36 percent in the 1990s, and 1.15 percent in the 2000s.

To explore how CE consumption might evolve to 2050, we use projections for population and GDP (in PPP 2005 constant prices) from the Shared Socioeconomic Pathways (SSP) database developed by the International Institute for Applied Systems Analysis (IIASA).[10] To provide a benchmark, we focus on the so-called 'middle ground' scenario (SSP2) for both GDP and population data. Over the period 2009–2050, the SSP2 projects annual global GDP growth of 3.1 percent, with per capita GDP growth of 2.4 percent and population growth of 0.68 percent.

An important feature of Eq. (1) is its implied pattern of income elasticities for total food demand. While income elasticities of demand for individual food items generally decline as income rises (Timmer, Falcon, & Pearson, 1983), the shift in demand from starchy staples to livestock products may cause the income elasticity

6 Standard errors are in brackets.

7 For instance, the rise in China's imports of oilseeds (mainly soybeans), which was a major cause of China's agricultural trade deficit since the late 2000s, can be explained by the expansion of its modern livestock sector—which increased demand for protein feeds—along with rising consumer demand for vegetable oils (Fukase and Martin, 2016).

8 For instance, Gouel and Guimbard (2018) show a similar pattern of caloric consumption increase with income, which plateaus at annual income of around $25,000 in 2010 PPP prices (Figure 2, p.396).

9 The figures for the 1980s are not strictly comparable, since we have data only for 115 countries, with most former Soviet bloc countries not reporting.

10 https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

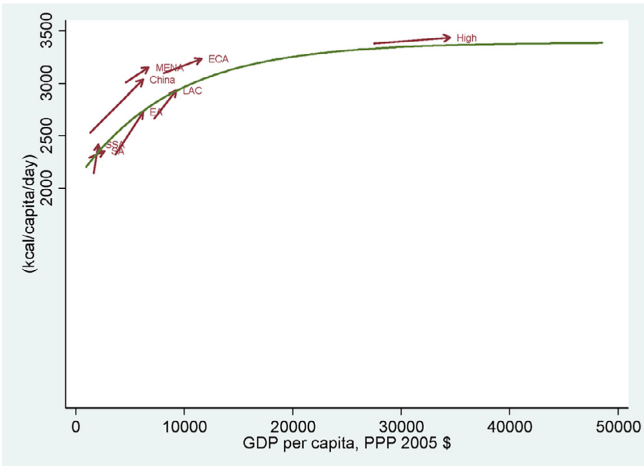

Fig. 2b. Changes in calorie consumption, 1992–2009. *Sources*: FAOSTAT and the World Development Indicators. *Notes:* The start and end points of the arrows are calorie consumption for 1992 and 2009. The country labels are placed at the ending points.

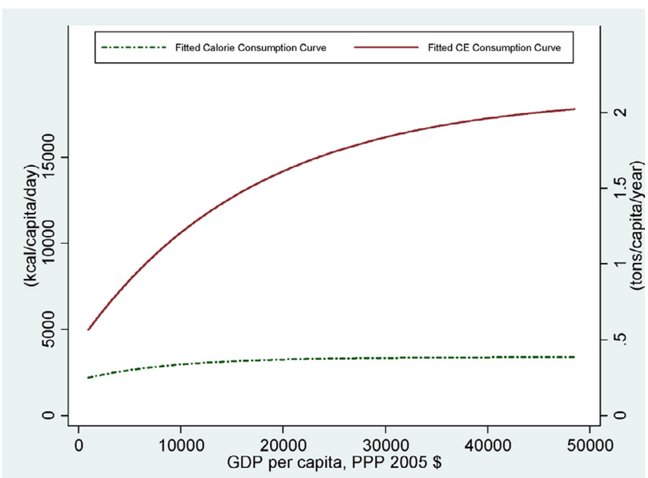

Fig. 2c. Calorie vs. CE consumption, 1992–2009. *Note*: Adopted following Fukase and Martin (2016).

of total food demand measured in resource requirements to rise over some range. As shown by Gouel and Guimbard (2018), the elasticity of demand for starchy staples is generally low, even for low-income consumers, while the elasticity of demand for livestock products is around 0.5, or higher, for low- to middle-income households. The income elasticities used by Baldos and Hertel (2012, p.12) show a similar pattern, with the income elasticities of demand for livestock products generally two or more times higher than for crops in low- and middle-income countries. These elasticities are consistent with increasing income elasticities of demand for total food as the animal-product share of consumption rises over this range.

Fig. 3 plots the income elasticity of food demand implied by Eq. (1) with respect to PPP GDP per capita for our 134 sample countries. It presents the arc elasticity defined as the change in the log of CE consumption divided by the change in the log of GDP between 2009 and 2050. Specifically,

$$\alpha = \frac{Ln\left(\widehat{Cons}_{2050}\right) - Ln\left(\widehat{Cons}_{2009}\right)}{Ln(GDP_{2050}) - Ln(GDP_{2009})}$$

where $Ln\left(\widehat{Cons}_{2050}\right)$ and $Ln\left(\widehat{Cons}_{2009}\right)$ are the logs of predicted per capita CE consumption computed using Eq. (1) for 2050 and 2009, while $Ln\ (GDP_{2050})$ and $Ln\ (GDP_{2009})$ are the logs of per capita GDP for the same years taken from the SSP database. In Fig. 3, the income elasticities are shown at the GDP of 2030 which is the mid-point of the years 2009 and 2050.

A striking feature of this graph is the inverted-U shape of the income elasticity of demand for total food as income rises. This shape contrasts with the previous studies which showed that the income elasticity for food is largest in the poorer countries and declines in magnitude with income (e.g., see Clements (2019), Gao (2011) and Muhammad, Seale, Meade, and Regmi (2011) for studies using International Comparison Data (ICP); Zhou and Yu (2014) for a meta-analysis on the calorie-income elasticity).

Our different elasticity pattern arises because we are not dealing with an individual food, but a mix of products that changes as income per capita rises. At very low levels of income, where staple foods predominate in the diet, the dominant feature of dietary transformation is shifts from coarse grains and root crops to fine grains such as rice or wheat (Timmer et al., 1983, p.29), we estimate the income elasticity to be relatively low in this range; it rises as income increases to middle-income levels and consumers shift from diets dominated by staple foods to diets including more animal products; peaks at around 0.42 at a PPP GDP of around $10,000; and then decreases as per capita income continues to grow. Evaluated at projected income levels in 2030, Fig. 3 shows that income elasticities in several populous countries, such as India

Table 1
Changes in CE Food Demand, 1980–2050.

Evolution of CE Food Demand, 1980–2009							
	CE Food Demand				Annual Average CE Food Demand Growth		
	Change	Initial year	Last year	Total	Per capita	Population	Per capita share
	(mil. Tons)	(mil. Tons)	(mil. Tons)	(%)	(%)	(%)	(%)
1980–1991	864	2999	3863	2.30	0.55	1.75	23.9
1992–2000	817	4590	5407	2.05	0.69	1.36	33.7
2001–2009	878	5455	6333	1.87	0.72	1.15	38.5
Projected Changes in CE Food Demand, 2009–2050							
	CE Food Demand				Annual Average CE Food Demand Growth		
	Change	Initial year	Final year	Total	Per capita	Population	Per capita/Total
	(mil. Tons)	(mil. Tons)	(mil. Tons)	(%)	(%)	(%)	(%)
2009–2050	7049	6899	13,948	1.72	1.03	0.68	60.2

Source: Authors' calculations.
Note: Annual CE food demand growth is computed as $(\ln food_{end\ year} - \ln food_{initial\ year})/n$ where n is the number of years. It is decomposed into population growth $(\ln pop_{end\ year} - \ln pop_{initial\ year})/n$ and per capita growth $(\ln \frac{food_{endyear}}{pop_{endyear}} - \ln \frac{food_{initialyear}}{pop_{initialyear}})/n$.

Table 2
Estimated Rates of Unconditional Convergence, %

	1980–1991	1992–2000	2001–2009	2009–2050 (proj.[a])
ß	0.28 (1.19)	0.25 (1.34)	−0.43** (−2.33)	−0.85*** (−17.20)
No. of Obs.	115	134	134	134

Source: Authors' calculations. The United States is used as the frontier economy.
Notes: *t-statistics* are in parentheses.
[a] GDP data for 2050 are taken from SSP2 (Leimbach et al., 2017).

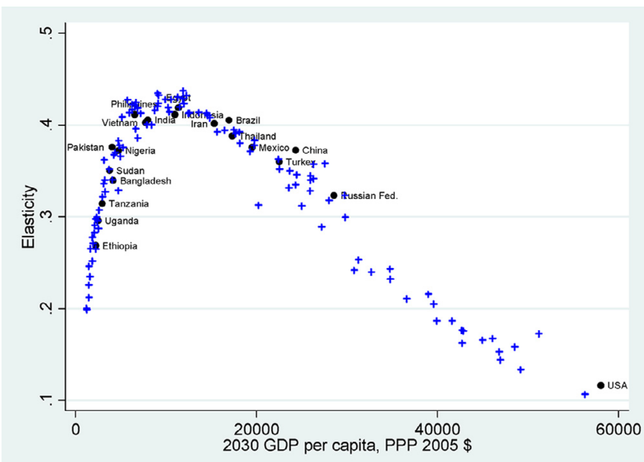

Fig. 3. GDP per capita and the income elasticity of food demand, 2030. *Source:* Authors' calculation based on Eq. (1) and the SSP2 data.

and Indonesia, are around their peak levels. While the elasticity is beginning to fall in key middle-income countries such as China and Turkey by 2030, this decline is relatively gradual, and income elasticities remain far above their levels in high-income countries. The elasticities for many SSA countries such as Nigeria, Ethiopia, Tanzania and Uganda would still be on the rise in 2030. At higher income levels, the shift into livestock products is complete and the tendency for all income elasticities of demand for food to decline (Timmer et al., 1983, p.57) results in elasticities of 0.1 or lower in such high-income countries as the United States.

The last row of Table 1 reports the estimated CE consumption changes between 2009 and 2050. Using the middle-ground GDP and population projections from the IIASA SSP, per capita CE consumption in 2050 was computed using 2050 GDP projections at the country level, multiplied by 2050 population projections and added up to the global level to compute global food demand in 2050. Global CE food consumption is projected to grow at an average of 1.72 percent per year between 2009 and 2050, more than doubling food demand (up 102 percent) by 2050. Our estimate is much larger than the increases in food demand estimated in many such studies, particularly the 50 percent increase in food and other agricultural demand projected by FAO (2017); the 47 percent by Gouel and Guimbard (2018); the 60 percent by IFPRI (2017); and the 69 percent by Pardey, Beddow, Hurley, Beatty, and Eidman (2014). But it is in line with Tilman, Balzer, Hill, and Befort (2011) who projected a food demand increase of 100 to 110 percent between 2005 and 2050, considering the agricultural resource costs of crops used both for human foods and livestock/fish feeds.

Our analysis suggests that considerable care is needed in interpreting estimates of the growth of total food demand. If the focus is on calories delivered to the consumer, as in Gouel and Guimbard (2018), where food is measured in calorie equivalents of food consumed, the weight on livestock products is likely to be much smaller than—as in this paper—when the focus is on the resource cost of food consumed and livestock products receive a much larger weight.

Decomposing the projected food demand growth rate, we see an increase in the growth rate of per capita consumption—to 1.03 percent per year—and a sharp decline in the population growth rate, to 0.68 percent per year on average. Overall, the last column of Table 1 reveals an increasingly important role of per capita income growth relative to population growth in contributing to global food demand growth. Between 2009 and 2050, about 60 percent of projected food demand growth comes from per capita demand growth, as against 24 percent in the 1980s, 34 percent in the 1990s and 39 percent in the early 2000s. Baldos and Hertel (2016, p.31) also find an increase in the importance of income relative to population growth, concluding that income growth will, for the first time in history, rival population growth as a source of demand for food.

3. Quantifying convergence and its impact on food demand

Accelerated growth in developing countries has resulted in a dramatic fall in the global GDP share of the Group of Seven (G7) countries, from almost two-thirds in 1990 to less than half today (Figure 23, Baldwin, 2016). To investigate whether developing countries have systematically been growing more rapidly than higher income countries, we regress per capita annual GDP growth rates (Δlny_i) for country *i* on country *i*'s initial log GDP (lny_i) relative to the country at the technological frontier (lny_{US}) which is almost invariably assumed to be the United States:

$$\Delta lny_i = \gamma + \beta(lny_i - lny_{US}) \qquad (2)$$

The results in Table 2 show that the coefficients on the convergence terms for the final two decades of the last millennium are positive—implying unconditional divergence, rather than convergence—but not statistically significant. In contrast, the convergence term for 2001–2009 is negative and significant at the 5 percent level, suggesting countries' incomes started to converge in the first decade of the new millennium. The estimated rate of convergence of −0.43 percentage points in this period is, however, still around a quarter of the estimate of −1.57 percentage points for unconditional convergence among OECD members estimated by Dowrick and Nguyen Eq. (1) p.1018 (1989). The last column of Table 2 reveals that the SSP2 GDP projections for the middle of the century embody a trend of much more rapid convergence (−0.85 percentage points) than in the 2001–2009 period.

To estimate the extent to which the income convergence embodied in the SSP2 would affect growth in food demand, we perform a counterfactual simulation of uniform per capita growth in all countries at the rate that would result in world income being the same in 2050 as under SSP2. World GDP, per capita GDP and population are specified as growing at 3.1 percent, 2.4 percent and 0.68 percent per year respectively under both scenarios. Table 3 compares the food demand increases normalizing food demand in 2009 at 100 to facilitate comparison. The results are decomposed by region with the ten countries that may contribute most to the difference broken out individually.

Table 3
Contribution to CE Consumption Changes, 2009–2050, %

	SSP2 Change (%)	Uniform Change (%)	Difference (%)
Developing as a group	**95.3**	**69.8**	**25.4**
SA	30.8	20.4	10.4
Of which India	24.9	15.9	8.9
Of which Bangladesh	2.0	1.1	0.9
Of which Pakistan	3.2	2.8	0.4
China	17.1	9.5	7.5
SSA	18.9	14.3	4.6
Of which Nigeria	5.2	3.9	1.3
Of which Ethiopia	1.5	0.9	0.6
Of which Tanzania	1.2	0.8	0.3
EA	9.7	6.8	2.8
Of which: Indonesia	4.4	2.6	1.8
Of which: Vietnam	1.3	0.8	0.5
ECA	4.6	4.3	0.3
MENA	5.3	5.2	0.1
Of which: Egypt	2.0	1.7	0.3
LAC	8.9	9.3	−0.3
High-Income as a group	**6.9**	**7.9**	**−1.0**
Total	**102.2**	**77.7**	**24.4**

Source: Authors' simulation results based on a sample of 134 countries.
Note: CE food demand in 2009 is normalized to 100.

The result reveals a striking difference in food demand changes coming from the different income growth patterns, with a much larger CE food demand increase under the convergent SSP2 scenario (102 percent) than under the non-convergent uniform growth scenario (78 percent). Table 3 shows that developing countries as a group dominate the increase in food demand. Out of a 102 percent food demand increase, 95 percentage points are attributable to developing countries in the SSP2 scenario, while 70 percent of the 78 percent increase in food demand under the uniform growth scenario comes from them. India, followed by China, Indonesia and Nigeria, are the largest contributors to the difference in the two scenarios, suggesting that whether these populous middle-income countries converge matters greatly for global food demand. As shown in Fig. 3, the large impact of income convergence for middle-income countries is partly attributable to their relatively high-income elasticities of food demand given the greater agricultural resource use needed for dietary upgrading.

Table 3 shows that high-income countries as a group would contribute modestly to global food demand increases (6.9 percent in SSP2 and 7.9 percent in the uniform growth scenario) partly due to slower population growth. While the counterfactual uniform growth scenario involves shifting world income from developing to high-income countries in 2050, the resulting increase in food demand in high-income countries is small (1.0 percentage point) due to the low income elasticities in these economies. Consistent with Cirera and Masset (2010), our results show that a decrease in between-country income inequality resulting from convergence increases aggregate food demand, given the same level of aggregate income.

One key question is how much confidence we can have in our finding that convergent growth results in higher global demand for food than growth at a uniform rate across countries. This, in turn, depends on the confidence we have in the parameters of the demand and convergence equations. To examine this question, we focus on a simulation where the only differences in growth rates across countries are given by the rate of convergence (−0.85) observed in the SSP2 projections to 2050.[11] We first projected growth in GDP and in food demand deterministically to 2050 and then performed a counterfactual simulation with the uniform growth rate that would result in the same value of world GDP in 2050. Finally, we used a Monte Carlo simulation including pseudo-random stochastic terms reflecting our uncertainty about the parameters to estimate expected global food consumption in 2050 and to put confidence intervals on our estimate of growth under convergence.

Fig. 4 shows the key results of this analysis. Under the uniform growth scenario, food demand grows to 10,670 million tons, as shown by the cross-hatched bar With incomes converging at the rate implied by the SSP2 scenario (that is at a rate that reduces the gap between lower income economies and the United States by 0.85 percent per year), food demand grows to 12,035 million tons by 2050. With 4000 replications, the kernel density of the projections was almost indistinguishable from normal, with a standard deviation of 546 million tons. The resulting 95 percent confidence interval for world food demand under convergence is from 10,966 to 13,106 million tons. Even the lower bound of this confidence interval is above the uniform growth outcome of 10,670 million tons, suggesting that we can be quite confident in our conclusion that income convergence matters for world food demand.

3.1. Convergence and correlations in forecasting food demand growth

The analysis in the previous section is undertaken in levels, which avoids any approximation errors, but does not allow us to understand why the results are so different between the uniform growth and convergent scenarios. To understand the sources of the much higher growth in food demand under the convergent SSP2 scenario, we turn to a share-weighted log-difference approach.

We define per capita food demand growth under the SSP2 scenario, q as:

$$q = \sum S_i \cdot \alpha_i \cdot y_i \quad (3)$$

where S_i is the share of country i in global food demand, α_i is the arc income elasticity for country i, and y_i is the rate of per capita economic growth in country i.

If the α and y variables are independent,

$$\Sigma S_i.\alpha_i.y_i = \alpha.y \quad (4)$$

where $\alpha = \Sigma S_i.\alpha_i$ and $y = \Sigma S_i.y_i$

If α and y are not independent, a second-order Taylor Series approximation around $\alpha.\,y$ yields:

$$q = \alpha.y + \sum S_i(\alpha_i - \alpha)(y_i - y) \quad (5)$$

This equation makes clear that correlations between growth rates and income elasticities could affect food demand growth.

Another potentially important difference between the convergent growth scenario and the uniform growth scenario arises from the different weights involved in aggregating income and food demand. When we calculate the growth of global income, we are implicitly weighting by GDP shares, W_i, rather than by food shares S_i. In the uniform growth scenario, the uniform growth rate is $y^u = \sum W_i.y_i$ where W_i is the GDP weight of country i. The estimated food demand using this approach is therefore $q^u = \alpha[\Sigma W_i.y_i]$.

Adding and subtracting food demand growth under the uniform growth scenario, q^u, and recalling that $\alpha \cdot y = \alpha[\sum S_i \cdot y_i]$, we obtain:

[11] See Section 5 for more detailed description of the 'pure convergence scenario'.

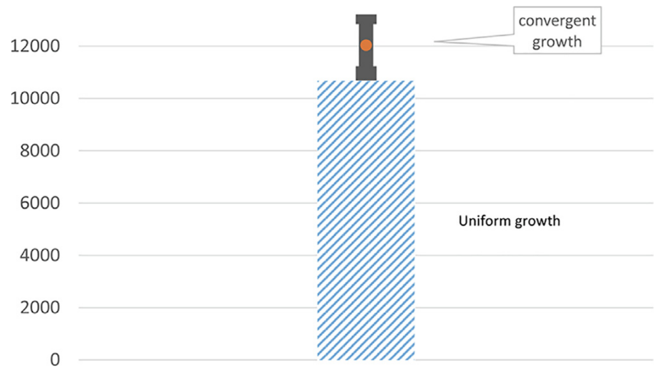

Fig. 4. Food demand in 2050 after uniform and convergent growth, million tons CE.

$$q \approx q^u + \alpha\left[\sum (S_i - W_i) \cdot y_i\right] + \sum S_i(\alpha_i - \alpha)(y_i - y) \quad (6)$$

This shows that the difference in food demand growth between the SSP2 and the uniform growth scenarios can be decomposed into (i) the sum of the cross-products between growth rates and differentials between countries' income shares and food consumption shares $\alpha[\sum (S_i - W_i) \cdot y_i]$, and (ii) the covariance between the income elasticities and the growth rates $\sum S_i(\alpha_i - \alpha)(y_i - y)$.

Due to Engel's law, low income countries tend to spend more of their income on food than richer countries ($S_{low} - W_{low} > 0$, $S_{high} - W_{high} < 0$). Thus, when income growth is convergent ($y_{low} > y_{high}$), the term (i) is positive while it becomes negative when income growth is divergent ($y_{low} < y_{high}$). With income convergence, component (ii) resulting from the correlation between income growth and income elasticities ($\sum S_i(\alpha_i - \alpha)(y_i - y)$) is also positive, because the income elasticities of demand in developing countries tend to be above average, ($\alpha_i - \alpha > 0$) and their income growth is also higher under convergence ($y_i - y > 0$). High-income countries also tend to contribute positively to the term, since their elasticities of demand and growth rates tend to be below average, $\alpha_i - \alpha < 0$ and $y_i - y < 0$ respectively. However, the inverted-U shaped pattern of income elasticities shown in Fig. 3 reduces this component, because some of the lowest-income economies have lower elasticities than the average.

Introducing global population growth into Eq. (6) yields:

$$q^t = q + n \quad (7)$$

where q^t is global growth in food demand and n is the food-share-weighted population growth rate.

The resulting decomposition of food demand growth between 2009 and 2050 is summarized in Table 4.

Total global food demand growth between 2009 and 2050 turns out to be 70 percent in log-difference terms under the SSP2 scenario and 58 percent under the uniform growth scenario. These results are consistent with the 102 percent increase in food demand in the SSP2 scenario in the previous section ($e^{0.70} - 1 \approx 1.02$) and the 78 percent increase under the uniform growth scenario ($e^{0.58} - 1 \approx 0.78$). While food-weighted population is found to grow by 23 percent in log-difference terms for both scenarios, food-weighted per capita demand growth under SSP2 of 48 percent in log-difference terms is much greater than the 36 percent in log-difference terms under the uniform growth scenario. The difference can almost entirely be explained by the two components identified above:(i) the correlation between income growth rates and the share differentials (7 percent in log-difference terms) and (ii) the component resulting from the relationship between income growth and income elasticities (4.4 percent in log-difference terms). For very specific reasons, the growth rates of per capita demand growth and population growth in this section

Table 4
Decomposition of Food Demand Growth, 2009–2050, Del log %.

	SSP2 Scenario (%)	Uniform Scenario (%)
Food-weighted Per Capita Demand Growth	**48**	**36**
Of which $\beta[\sum (S_i - W_i.y_i)]$	7.0	
Of which $\sum S_i(\alpha_i - \alpha)(y_i - y)_i$	4.4	
Food-weighted population growth	**23**	**23**
Total Global Food Demand Growth	**70**	**58**

Source: Authors' simulation results based on a sample of 134 countries.
Note: Percentage changes are based on log-differences.

differ from the descriptive statistics shown in Table 1. The decomposition in Table 1 was population-share-weighted for comparability with the existing literature, while the population growth rates in Table 4 are food-demand-share weighted to allow them to be added to the food-share-weighted income growth terms. Dividing the 23 percent population impact in log-difference terms in table 4 by the 41 years of the projection period reveals a lower estimate (0.56 percent per year) of the impact of population growth than in Table 1 (0.68 percent per year).

4. Modeling food supply

While our primary focus in this paper is on economic convergence and food demand, an obvious question is how the increase in demand for food associated with convergence might be met, and what the implications for food prices might be. In this section, we use a parsimonious representation of supply based on per capita GDP and land availability. This model captures three important stylized facts—that agricultural output rises with a country's land endowment; that higher economy-wide productivity increases output; and that agricultural output increases by less than total output as the economy grows (Martin & Warr, 1993). We recognize that agricultural research and development (R&D) is an important influence on productivity (Fuglie, 2017), but lack the data on stocks of accumulated knowledge resulting from R&D to include this variable directly in the regression equation. This effect of concern to us is, however, captured to the extent that increases in national income increase countries' ability to invest in agricultural R&D.

Between 1992 and 2012, the world's arable land increased slightly, from 1523 million hectares to 1562 million hectares (FAOSTAT). However, arable land per capita declined in all regions due to a combination of population growth and higher productivity of the land in use (Figure 6, Fukase & Martin, 2017). While arable land per capita has declined, the world has been successful in producing more food per person on average, primarily because of agricultural productivity growth.

Fukase and Martin (2016) estimated the following simple food production model in cereal equivalents as a function of income and land endowment per capita using a data set for 1980–2009:

$$z = 0.23 + 0.0039\, x^{0.62} \cdot l^{0.32} \quad (8)$$

[0.11] [0.0043] [0.10] [0.037]

where z is CE production per capita, x is PPP GDP per capita in 2005 constant prices, l is hectares of agricultural land per capita and the figures in square brackets are Standard Errors.[12] The exponent on the income per capita term is positive as higher agricultural productivity, associated with the higher economy-wide productivity

[12] Following Rask and Rask (2011), hectares of agricultural land per capita are defined as a sum of arable land, land in permanent crops, and one-third of land in permanent pasture.

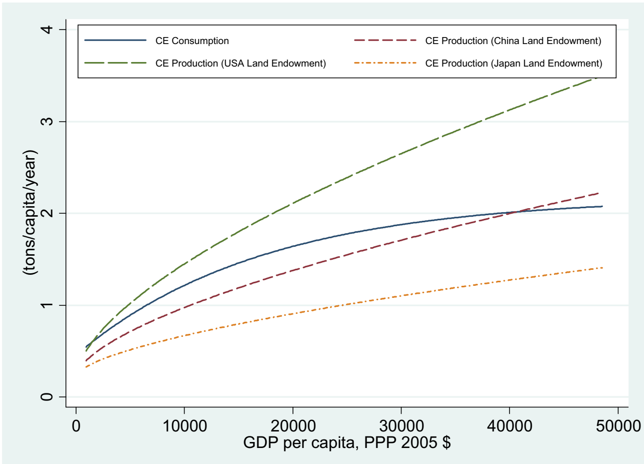

Fig. 5. CE production, consumption vs. income by land endowment. *Source:* Adopted from Fukase and Martin (Figures 10abc, 2014). *Notes*: The land endowments for China, Japan and the United States used in this figure are 1980–2009 averages, which are 0.21 ha, 0.04 ha and 0.99 ha per person respectively. Following Rask and Rask (2011), hectares of agricultural land per capita are defined as a sum of arable land, land in permanent crops, and one-third of land in permanent pasture.

that increases income levels, raises agricultural production and feeds into higher expenditures on agricultural research (Adetutu & Ajayi, 2020). The positive relationship between income and agricultural production is likely to reflect not only higher yields per hectare but also better infrastructure and marketing know-how associated with higher income. The exponent on the agricultural land is positive as land-abundant countries tend to produce and export land-intensive commodities such as agricultural products.

Using the parameter values from Eq. (8), Fig. 5 shows the estimated CE production curves evaluated at different land endowments of selected countries, namely, the United States (land abundant), Japan (land scarce) and China (relatively land scarce) together with the global CE consumption curve (adapted from figures 10abc, Fukase & Martin, 2014).

The figure suggests that agricultural production per capita rises with income; that the shape of the production curve is concave, but substantially less concave than the consumption curve, revealing close to a linear relationship between income and production; and that countries with higher land endowments tend to produce more food given the same level of income. The figure also suggests that land abundant countries such as the United States tend to produce more food than they consume and to be exporters of food at almost all income levels. In contrast, land-scarce countries such as Japan are likely to consume more food than they produce, being food importers throughout their income levels. For relatively land scarce countries such as China, the concavity of the consumption curve implies that their consumption growth may be faster than production growth for a wide range of income, which in turn may contribute to rising net imports.

5. Convergence and food demand and supply to 2050

Using the intermediate PPP GDP[13] and population projections for 2050 from the SSP database (SSP2) (Leimbach, Kriegler, Roming, & Schwanitz, 2017), we simulate CE consumption and production to 2050. We use projections of arable land kindly provided by Jelle Bruinsma, which show a declining land endowment per capita towards 2050 (Figure 4.3, Alexandratos & Bruinsma, 2012). We consider a series of convergence scenarios on the demand side and assume that the change in production follows the pattern reflected in the parameters in Eq. (8). Thus, our simulation scenario on the supply side does not reflect potential impacts on productivity resulting from such additional constraints as climate change and environmental degradation. While there are significant variations in the accuracy of regional projections,[14] models of this type tend to perform better at the aggregate level (Hertel et al., 2016; McCalla & Revoredo, 2001). We therefore focus on aggregate measures in this section.

The CE food consumption and production in 2050 are estimated using the SSP2 projection data and the parameter values in Eqs. (1) and (8) at the country level, multiplied by projected population to compute the national consumption and production, and added up to the global level.[15] Table 5 shows the results of estimated CE production and CE consumption under different convergence scenarios.

The results for the SSP2 scenario in columns 1–2 show that CE production would increase by 112 percent while CE consumption would increase by 102 percent over the period 2009 to 2050 (our base scenario). The gap of around 4.8 percent in log-difference terms between our supply and demand would imply modest downward pressure on prices. If we accept the estimates of the three relevant elasticities of response[16] from Hertel et al. (2016), this gap would translate into a price decline of around 4.1 percent.

To measure the extent to which the convergence embodied in the SSP2 scenario is affecting food demand, the second column of Table 5 reports the results of the counterfactual uniform growth scenario of all countries growing at the same rate, taking global income to the same level in 2050 as the SSP2 scenario. This implies annual global GDP growth of 3.1 percent in both scenarios. The move to a uniform growth scenario causes a much larger decline in food demand growth (from 102 percent to 78 percent) than that in food supply (from 112 to 104 percent). The resulting gap between supply and demand of 13.9 percent in log-difference terms would lead to a price decline of 12.0 percent. Comparing the results between the SSP2 and uniform growth scenarios, the net effect on prices of moving from the uniform growth scenario to the SSP2 scenario is to increase prices by 7.9 percentage points. The growth convergence inherent in the SSP2 scenario is therefore partly offsetting what would otherwise have been substantial downward pressure on world food prices.

A question arises whether our results might be driven mainly by the outperformance of two populous Asian giants, namely China and India. The next two columns of Table 5 repeat the same simulations as those in columns 1–2, excluding China and India from our sample. The qualitative results are essentially unchanged and our results appear to be robust to the inclusion of China and India.

The differential GDP growth rates embodied in the SSP2 scenario may reflect features of the data set other than convergence.

[13] One caveat in our analyses is that we rely our GDP assumptions on the SSP database and do not consider the potential growth slowdown identified by recent research (e.g., Laborde and Martin, 2018).

[14] See Appendix Figures A1-A2 (Fukase & Martin, 2017) for a validation exercise to examine how the model could replicate the past by region.

[15] Since there is an overestimate of CE consumption and an underestimate of CE production in the initial year, we remove these residuals by adjusting them multiplicatively so that initial CE consumption and production match the actual 2009 CE consumption and production. We apply the same multiplicative terms for the years 2030 and 2050 so that this adjustment preserves the percentage changes. There exists a slight gap between actual CE consumption and production in 2009 (about 0.9 percent) due to the missing countries in our sample. We adjust initial supply and demand at the mid-point of the actual supply and demand gap.

[16] The demand and supply elasticities implied in global agricultural models tend to vary substantially (Table 3, Hertel et al., 2016). The emulator elasticities are: for food demand (−0.29), for the response of output due to substitution between land and other inputs (0.51), and for land supply (0.36). Together they imply a flexibility of price response to a proportional gap between supply and demand in the order of 0.86 [$\frac{1}{1.16} \approx 0.86$]. Thus, the gap of around 4.8 percent in log-difference terms between our supply and demand assumptions implies a price decline of about 4.1 percent.

Table 5
Supply and Demand Gaps and Price Impacts, 2050.

	Base		Without China and India		Pure Convergence		Strong Convergence		2001–2009 Convergence	
	SSP2	Uniform (3.1%)	SSP2 w/o China/ India	Uniform (2.5%)	Pure Convergence	Uniform (2.7%)	Dowrick & Nguyen	Uniform (3.8%)	2001–2009	Uniform (×2.1%)
CE Consumption 2050 (mil. tons)	12,858	11,301	8331	7336	12,035	10,670	14,886	12,233	10,570	9953
CE Production 2050 (mil. tons)	13,497	12,981	8620	8221	12,287	11,768	15,970	15,011	10,771	10,515
CE Consumption Change (%)	102	78	90	68	89	68	134	92	66	56
CE Production Change (%)	112	104	98	88	93	85	151	136	69	65
Supply & Demand Gap (in log-dif.)	4.8	13.9	3.9	11.9	2.1	9.8	7.0	20.5	1.9	5.5
Price Change (in log-dif.)	−4.1	−12.0	−3.4	−10.2	−1.8	−8.4	−6.0	−17.6	−1.6	−4.7
Net price change (in log-diff.)	7.9		6.9		6.6		11.6		3.1	

Source: Authors' simulation results.

If, for instance, they reflected a bias towards more rapid growth in the middle-income countries with the highest income elasticities, it would generate more rapid growth in global demand than one with the highest growth rate among the countries with the lowest incomes. To focus more directly on the convergence issue, we construct an alternative scenario in which country growth rates relative to the United States are determined solely by the convergence rate embodied in the SSP2 ('Pure convergence' scenario). Specifically, each country's annual growth rate is computed as 1.2–0.85 $[lny_i - lny_{US}]$ where lny_i is the initial log GDP for country i, lny_{US} is the initial log GDP of the United States and 1.2 is the projected growth rate for the United States in SSP2. Since this scenario would lead to a lower world GDP growth of 2.7 percent, in parallel to the base comparison, we construct a uniform growth scenario in which the world economies grow at uniform 2.7 percent per year. The results are shown in Columns 5–6 in Table 5. Similar to the SSP2 scenario, the impact of convergence is larger on the demand side relative to the supply side, albeit to a lesser degree. The net effect of the convergence relative to the uniform growth scenario is to increase prices by 6.6 percentage points, or slightly less than the SSP2 scenario.

Columns 7–8 of Table 5 consider a strong convergence scenario. We explore what would happen if growth rates were to converge as rapidly as the OECD countries between 1950 and 1985 with convergence rate of −1.57 (Dowrick & Nguyen, 1989) which is nearly as twice that in the SSP2 scenario of −0.85 ('Middle of the Road' scenario). This scenario would result in an average annual world GDP growth rate of 3.8 percent. The increase in food demand of 134 percent under the strong convergence scenario is 45 percent above the comparable uniform growth scenario (92 percent)—a much larger difference than the 30 percent difference between these two scenarios under the pure convergence scenario modeled on SSP2. A much greater impact of convergence in demand than in supply would result in the net impact on price increase of 11.6 percentage points relative to the uniform growth scenario, which is nearly double relative to the scenario which assumes SSP2 convergence rate.

In the final two columns of Table 5, we also consider a lower rate of convergence, with the same rate of convergence as in 2001–2009 of −0.43, which is about half that of our base scenario of −0.85 (the last two columns). The lower rate of convergence would lead to a lower average annual world GDP growth rate of 2.1 percent. With relatively low economic growth and convergence rate, the net impact on price increase would be 3.1 percentage points relative to the uniform growth scenario, about a half compared to the scenario with SSP2 convergence rate.

Overall, we find a clear pattern that the impact of income convergence on world food demand is substantially larger than its impact on supply. As a result, income convergence is likely to contribute to upward pressure on food prices. However, in all our scenarios assuming historical patterns of productivity growth, the pressure on food demand caused by convergence appears likely to be reasonably manageable. There may, of course, be other reasons—such as the high emission intensity of key agricultural products such as beef—to try to identify ways either to reduce emissions or to reduce distorting subsidies on some products with high emission intensities (Mamun, Martin, & Tokgoz, 2019).

6. Conclusions

Using a simple econometric model focusing on key drivers (income growth, population growth, dietary change, productivity growth and land endowment), this article explores the implications of income convergence in influencing global food demand. We aggregate food into a single commodity measured by resource-based cereal equivalents (CE) (Rask & Rask, 2011; Yotopoulos, 1985), which allow us to evaluate the differential growth rates of consumption and production of food at different levels of income. Because of the much higher costs of producing livestock products, this resource-cost-based measure of food demand is much more responsive to income growth than alternative measures based on final calories consumed.

Using the GDP and population projections from the SSP2 data set, we find that CE food demand would roughly double, increasing by 102 percent between 2009 and 2050. The decomposition of demand growth into per capita demand growth and population growth suggests that demand growth driven by per capita income growth is likely to be more important than growth driven by increasing population over the period to 2050. This contrasts with the historical pattern in which population growth dominated consumption per capita growth in influencing food demand growth and makes the question of impacts of economic convergence more important than when demand was dominated by population growth.

The implications of income convergence for food demand seems a timely question, given the apparent reversal of fortunes in moving from the Great Divergence (Pritchett, 1997) to the Great Convergence which started around 1990 (Baldwin, 2016). We find that the coefficient for unconditional income convergence in our sample countries was not significant in the 1980s or 1990s but became significant in the first decade of the 2000s, when developing countries grew, on average, much more rapidly than the developed countries. We also find that the rate of income convergence using the middle-ground GDP projections from the SSP database (SSP2) between 2009 and 2050 is about twice as rapid as the last decade, although still about half the rate estimated by Dowrick and Nguyen (1989) for the OECD countries in their post-war growth era of 1950–1985.

A series of simulation results reveal that the impact of convergence on food demand can be substantial. The rise in demand of our base scenario (102 percent), which embodies the trend of income convergence from SSP2, is about one-third greater than that under the counterfactual non-convergent growth scenario in which all the countries experience the same growth rates (78 percent). The regional decomposition shows that developing countries as a group dominate the increase in food demand and that their income convergence does matter. We find that convergence by middle-income countries, especially such populous countries as India, China, Indonesia and Nigeria, is particularly important for global food demand. This is partly due to the inverted-U shaped pattern of income elasticities for aggregate food demand, with middle-income countries experiencing the largest income elasticities due to their dietary upgrading towards more resource demanding products.

On the supply side, the impact of convergence is much more muted than on the demand side, suggesting that convergence—if it continues to occur—will contribute to upward pressure on world food prices. Such increases are relative to a baseline which, like Baldos and Hertel (2016), may involve falling real food prices. Thus, meeting the additional demand associated with higher rates of economic convergence appears to be manageable if agricultural productivity growth continues in line with historical patterns.

Finally, while our minimalist approach is useful in highlighting the interplay of key drivers of food demand, supply and prices, it is important to remember that it is designed to answer 'what-if' questions regarding the impact of changes in convergence rates, rather than to provide predictions about future prices. Any such predictions require information on the entire set of influences on future food supply and demand, including changes in rates of technical change, impacts of climate change and policy changes affecting production and consumption. However, our framework is useful for highlighting the potentially important implications of economic convergence on demand, supply and the ability of the food system to deliver the food needed to meet the objectives of the Sustainable Development Goals.

Declaration of Competing Interest

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

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References

Abramovitz, M. (1986). Catching up, forging ahead, and falling behind. Journal of Economic History, (2), 385–406.

Adetutu, M. and Ajayi, V. (2020), 'The impact of domestic and foreign R&D on agricultural productivity in sub-Saharan Africa' World Development 125: 104690.

Alexandratos, N., & Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. ESA Working Paper, 12-03. Rome: Food and Agriculture Organization of the United Nations.

Anderson, K., Dimaranan, B., Hertel, T., & Martin, W. (1997). Asia-Pacific food markets and trade in 2005: A global, economy-wide perspective. *Australian Journal of Agricultural and Resource Economics, 41*(1), 19–44.

Baldos, U., Hertel, T. (2012). SIMPLE: a Simplified International Model of agricultural Prices, land use and the environment. GTAP Working Paper, 70, Purdue University.

Baldos, U., & Hertel, T. (2016). Debunking the 'New Normal': Why world food prices are expected to resume their long run downward trend. *Global Food Security, 8*, 27–38.

Baldwin, R. (2016). *The great convergence*. Cambridge: Harvard University Press.

Barro, R. (2015). Convergence and modernization. *Economic Journal, 125*, 911–942.

Baumol, W. (1986). Productivity growth, convergence, and welfare: What the long-run data show. *American Economic Review, 76*, 1072–1085.

Bhalla, S. (2017). *The new wealth of nations*. Noida: Simon and Schuster India.

Bodirsky, B. L., Rolinski, S., Biewald, A., Weindl, I., Popp, A., & Lotze-Campen, H. (2015). Global food demand scenarios for the 21st century. *PLoS One, 10*(11) e0139201.

Cirera, X., & Masset, E. (2010). Income distribution trends and future food demand. *Philosophical Transactions of the Royal Society, B, 365*, 2821–2834. https://doi.org/10.1098/rstb.2010.0164.

Clements, K. W. (2019). Four laws of consumption. *Economic Record, 95*(310), 358–385.

Dervis, K. (2012). World economy, convergence, interdependence, and divergence. Money, 15. http://www.imf.org/external/pubs/ft/fandd/2012/09/dervis.htm.

Dowrick, S., & Nguyen, D. T. (1989). OECD comparative economic growth 1950–85: Catch-up and convergence. *American Economic Review, 79*(5), 1010–1030.

FAO (Food and Agriculture Organization). (2017). The Future of Food and Agriculture: Trends and Challenges. Rome: Food and Agriculture Organization of the United Nations.

Fuglie, K. (2017). R&D capital, R&D spillovers, and productivity growth in world agriculture. *Applied Economic Perspectives and Policy, 40*(3), 421–444.

Fukase, E., Martin, W. (2014). Who will feed China in the 21st century? Income growth and food demand and supply in China. Policy Research Working Paper, 6926. Washington DC: World Bank.

Fukase, E., Martin, W. (2017). Economic growth, convergence, and world food demand and supply. Policy Research Working Paper, 8257. Washington DC: World Bank.

Fukase, E., & Martin, W. (2016). Who will feed China in the 21st century? Income growth and food demand and supply in China. *Journal of Agricultural Economics, 67*(1), 3–23.

Gao, G. (2011). World food demand. *American Journal of Agricultural Economics, 94* (1), 25–51.

Gerbens-Leenes, P. W., & Nonhebel, S. (2002). Consumption patterns and their effects on land required for food. *Ecological Economics, 42*(1–2), 185–199.

Godfray, H. C. (2011). Food for thought. *Proceedings of the National Academy of Sciences, 108*(50), 19845–19846.

Gollin, D., Lagakos, D., & Waugh, M. (2013). The agricultural productivity gap. *Quarterly Journal of Economics, 128*, 939–993. https://doi.org/10.1093/qje/qjt056.

Gouel, C., & Guimbard, H. (2018). Nutrition transition and the structure of global food demand. *American Journal of Agricultural Economics, 101*(2), 383–403.

Headey, D., Hirvonen, K., & Hoddinott, J. (2018). Animal sourced foods and child stunting. *American Journal of Agricultural Economics, 100*(5), 1302–1319.

Hertel, T. (2011). The global supply and demand for agricultural land in 2050: A perfect storm in the making?. *American Journal of Agricultural Economics, 93*(2), 259–275.

Hertel, T., Baldos, U. (2016). Global Change and the Challenges of Sustainably Feeding a Growing Planet. Springer.

Hertel, T., Baldos, U., & van der Mensbrugghe, D. (2016). Predicting long-term food demand, cropland use and prices. *Annual Review of Resource Economics, 8*(1), 417–441.

IFPRI (International Food Policy Research Institute). (2017). 2017 Global Food Policy Report. Washington DC: International Food Policy Research Institute.

Johnson, P., & Papageorgiou, C. (2020). What Remains of Cross-Country Convergence?. *Journal of Economic Literature, 58*(1), 129–175.

Korotayev, A., Zinkina, J., Bogevolnov, J., & Malkov, A. (2011). Global unconditional convergence among larger economies after 1998?. *Journal of Globalization Studies, 2*(2), 246–280.

Laborde, D., & Martin, W. (2018). Implications of the global growth slowdown for rural poverty. *Agricultural Economics, 49*(3), 325–338.

Leimbach, M., Kriegler, E., Roming, N., & Schwanitz, J. (2017). Future growth patterns of world regions–a GDP scenario approach. *Global Environmental Change, 42*, 215–225. https://doi.org/10.1016/j.gloenvcha.2015.02.005.

Maddison, A. (2010). Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD. http://www.ggdc.net/maddison/oriindex.htm

Mamun, A., Martin, W., & Tokgoz, S. (2019), Reforming agricultural support for improved environmental outcomes, IFPRI Discussion Paper 10891. Washington DC: International Food Policy Research Institute. Forthcoming in Applied Economic Perspectives and Policy.

Martin, W., & Warr, P. G. (1993). Explaining the relative decline of agriculture: A supply-side analysis for Indonesia. *The World Bank Economic Review, 7*(3), 381–401.

McCalla, A. F., & Revoredo, C. L. (2001). Prospects for global food security: a critical appraisal of past projections and predictions. Food, Agriculture and the Environment Discussion Paper, 35. Washington DC: International Food Policy Research Institute.

Muhammad, A., Seale, J. L., Meade, B., & Regmi, A. (2011). International evidence on food consumption patterns: an update using 2005 international comparison program data. USDA-ERS technical bulletin, 1929.

Nelson, G. C., Valin, H., Sands, R. D., Havlík, P., Ahammad, H., Deryng, D., ... Willenbockel, D. (2014). Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences, 111*(9), 3274–3279.

Pardey, P., Beddow, J., Hurley, T., Beatty, T., & Eidman, V. (2014). A bounds analysis of world food futures: Global agriculture through to 2050. *Australian Journal of Agricultural and Resource Economics, 58*(4), 571–589.

Preckel, P. V., Cranfield, J. A. L., & Hertel, T. W. (2010). A modified, implicit, directly additive demand system. *Applied Economics, 42*(2), 143–155.

Pritchett, L. (1997). Divergence, big time. *Journal of Economic Perspectives, 11*(3), 3–17.

Rask, K., & Rask, N. (2004). Reaching turning points in economic transition: Adjustments to distortions in resource-based consumption of food. *Comparative Economic Studies, 46*(4), 542–569.

Rask, K., & Rask, N. (2011). Economic development and food production–consumption balance: A growing global challenge. *Food Policy, 36*(2), 186–196.

Rimmer, M., & Powell, A. (1996). An implicitly additive demand system. *Applied Economics, 28*, 1613–1622.

Rodrik, D. (2011). The future of economic convergence. Proceedings, Economic Policy Symposium, Jackson Hole, Federal Reserve Bank of Kansas City, 13-52.

Tilman, D., Balzer, C., Hill, J., & Befort, B. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences, 108*(50), 20260–20264.

Timmer, C. P., Falcon, W., & Pearson, S. (1983). Food Policy Analysis. Baltimore: Johns Hopkins University Press.

United Nations. (2019). World Population Prospects: The 2019 Revision. New York: United Nations.

Valin, H. R., Sands, D., van der Mensbrugghe, G., Nelson, H., Ahammad, E., Blanc, B., ... Willenbockel, D. (2014). The Future of food demand: Understanding differences in global economic models. *Agricultural Economics, 45*(1), 51–67.

Wiebe, K. L., Herman, R., Sands, T., Andrzej, D., van der Mensbrugghe, A., Biewald, B., ... Willenbockel, D. (2015). Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters, 10*(8) 085010.

World Bank. World Development Indicators (WDI). (Accessed December, 2017). Washington DC: World Bank.

Yotopoulos, P. (1985). Middle-income classes and food crises: The "new" food-feed competition. *Economic Development and Cultural Change, 33*(3), 463–483.

Zhen, L., Cao, S., Cheng, S., Xie, G., Wei, Y., Liu, X., & Li, F. (2010). Arable land requirements based on food consumption patterns: Case study in rural Guyuan District, western China. *Ecological Economics, 69*, 1443–1453.

Zhou, D., & Yu, X. (2014). Calorie elasticities with income dynamics: Evidence from the literature. *Applied Economic Perspectives and Policy, 37*(4), 575–601.