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Global food security in 2050: the role of agricultural productivity and climate change

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In this paper, we examine how the complexities introduced by trends in agricultural productivity and climate change affect the future of global food security. We use a partial equilibrium model of global agriculture incorporating a food security module that links changes in the average dietary energy intake to shifts in the full caloric distribution, allowing us to compute changes in the incidence, headcount and average depth of malnutrition. After validating the model against an historical period, we implement a series of future scenarios to understand the impacts of key exogenous drivers on selected food security outcomes. Our results show improvements in global food security for the period 2006–2050. Despite growing population and increased biofuel demand, baseline income growth, coupled with projected increases in agricultural productivity lead to a 24 per cent rise in global average dietary energy intake. Consequently, the incidence of malnutrition falls by 84 per cent, lifting more than half a billion people out of extreme hunger. However, these results hinge heavily on agricultural productivity growth. Without such growth, there could be a substantial setback on food security improvements. Climate change adds uncertainty to these projections, depending critically on the crop yield impacts of increasing CO_2 concentrations in the atmosphere.

Key words: agricultural productivity, climate change, dietary energy, food security, long-run analysis.

1. Introduction

In the coming decades, greater *per capita* food consumption is expected in the wake of growing incomes in the developing world. The resulting shifts in consumption patterns from a diet high in starchy foods to one that is richer in protein, including meats and dairy products (Gerbens-Leenes *et al*. 2010) will have an important impact on global agriculture. Shifts in the types of foods consumed, from local towards Western foods, are also expected (Pingali 2007). Coupled with steady population growth in the future, the competition for crop output between direct consumption, and livestock feedstuffs and raw inputs to processed food industries will intensify. At the same time, the industrial demand for crops is expected to rise with the growing use of renewable fuels worldwide, especially for first generation biofuels which require food crop feedstocks (Fischer *et al*. 2009).

Over the past five decades, food availability has been greatly enhanced through productivity gains in the agricultural sector. Continuation of such trends will be critical to ensuring food security between now and mid-century, as population, incomes and biofuel use continue to grow. Total factor

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productivity – a measure of the growth in aggregate output relative to an index of all inputs – in both the global crop and livestock sectors actually rose over the past two decades (Ludena *et al*. 2007; Fuglie 2012). However, there are concerns on some fronts that crop yields for key staple grains may be reaching their biophysical limits in some regions (Alston *et al*. 2009). This could have an adverse effect on global food availability and prices. The future trajectory of crop yields will also be affected by climate change, although the precise impacts are uncertain and spatially heterogeneous. Depending on location, the temperature and precipitation impacts of climate change may cause crop yields to rise or fall (Tubiello *et al*. 2007). There is also the potential for crop yields to be enhanced via the fertilization effect of rising CO_2 concentrations in the atmosphere (Lobell and Field 2008).

In this paper, we examine how global food security in 2050 will be affected by the trends in agricultural productivity and the complexities introduced by climate change. We add to the growing literature, which examines long-run global food security issues. These studies are based on a variety of methods, including: expert opinion coupled with trend analysis (Alexandratos and Bruinsma 2012), integrated assessment models which heavily incorporate biophysical processes (Fischer *et al*. 2005; Tubiello *et al*. 2007; Schneider *et al*. 2011) and partial as well as general equilibrium economic models (Msangi *et al*. 2010; Nelson *et al*. 2010, 2014; Golub *et al*. 2012). However, most of these studies use limited metrics of food security, which only encompass average changes in *per capita* dietary energy consumption (DEC) in each region, whereas it is really the *distribution of caloric consumption* across the population that is most critical for food security. In addition, these studies are largely based on models which have not been validated against the past. By looking at the past prior to projecting into the future, we gain insights into the changing relative importance of each major driver of global food security, as well as boosting confidence in the resultant projections.

In light of the existing literature, this paper makes three contributions. First, we quantify not only the prevalence of food insecurity given the drivers of the global farm and food system, but also the average depth of such insecurity, by accounting for the full distribution of dietary outcomes in each world region. Second, we validate our food security module, looking back at history to assess how well our model replicates observed changes in caloric malnutrition outcomes. Third, we decompose historical and projected drivers of food security which enables us to comment on changes in the relative importance of each major driver, with emphasis on the contribution of agricultural productivity and climate change, as we move forward to 2050.

The rest of the paper is organized as follows. In section “Model and methods”, we discuss the model of global agriculture that we use to project changes in crop production and food consumption and introduce the food security module that we have developed to extrapolate nutritional outcomes from the changes in average food consumption. In section “Historical validation” and “Experimental design for future projections”, we outline the experiments. To evaluate the model and see how well it predicts food security metrics, we look back at the historical period 1991 to 2001 (section "Historical validation"). We then examine the future, projecting forward from 2006 to 2050 (section "Experimental design for future projections"). We implement a sequence of scenarios that are designed to help us understand the implications of agricultural demand and supply drivers on future nutritional outcomes. The results of our simulations are discussed in section "Results" while the final section offers a summary and some concluding remarks.

2. Model and methods

2.1. SIMPLE model

To project the broad changes in the global farm and food system over the period 2006 to 2050, we utilize the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE) (Baldos and Hertel 2013). It is a partial equilibrium model but unlike other global models, which are highly disaggregated, SIMPLE is designed to be as parsimonious as possible, while faithfully producing estimates of crop demand and supply at a global scale. Details of the model framework are discussed in the Supporting information provided online (Data S1). The model has been used in studies focusing on climate change mitigation and adaptation (Lobell *et al.* 2013) as well as model validation and evaluation (Baldos and Hertel 2013). In the latter study, it is shown to do remarkably well at capturing observed global changes in crop production, area, yield and price over the period: 1961–2006. For this paper, we introduce a disaggregated version of the model and assess nutritional outcomes for the 15 geographic regions (Supporting information, Data S2).

2.2. Food security module

To extract information on nutritional outcomes from SIMPLE, we introduce here a food security module. It has two main functions. First, it characterizes the distribution of dietary energy consumption within each region, which allows us to calculate the incidence, headcount and average depth of caloric malnutrition. Second, it links the food caloric content to *per capita* income which captures the shifts in the composition of food. Using linear regressions, we estimated a negative relationship between *per capita* income and food caloric content from food crops and processed foods. On the other hand, there is a small rise in caloric content from livestock as incomes rise (Supporting information, column C in Data S4). Lastly, the module relates changes in the average *per capita* DEC to shifts in its distribution and to corresponding changes in the incidence, headcount and average depth of caloric malnutrition for each region.

We rely on two key measures of food security, namely the malnutrition incidence and the malnutrition gap. The former measures the prevalence of undernourishment by reporting the fraction of population whose daily dietary energy intake is below the minimum requirement. The latter captures the intensity of food deprivation, which is the average dietary energy deficit that an undernourished person needs to close to satisfy the minimum requirement (FAO 2012). In the literature, it is common to focus on changes in malnutrition incidence (Alexandratos 2010; Alexandratos and Bruinsma 2012). However, this measure ignores the variations in dietary energy deficits faced by malnourished persons. By reporting the malnutrition gap, we can examine the differences in the average depth of hunger across regions and see how the average depth changes within a region.

Mathematically, the malnutrition index and gap are equivalent to the poverty index and gap measures as proposed by Foster *et al.* (1984). Given this, we can use the concept of poverty-growth elasticities to link these measures to the average *per capita* dietary energy intake. Widely used in the poverty literature, these growth elasticities measure the per cent changes in the indices of poverty and poverty gap given a 1 per cent change in average *per capita* income (Bourguignon 2003; Lopez and Serven 2006). To apply this concept in the case of dietary energy, we assume that the distribution of *per capita* dietary energy consumption is lognormal. This is consistent with the traditional assumption used by FAO regarding the distribution of dietary energy intake within a country (Neiken 2003). The following equations are used to calculate the growth elasticities for the malnutrition index (ε_{MI}) and the malnutrition gap index (ε_{MGI}). They characterize the per cent change in these indices in the wake of a 1 per cent rise in average dietary energy intake:

$$\varepsilon_{MI} = -\frac{1}{\sigma}\frac{\tau}{\pi}\left[\frac{\ln(w/y)}{\sigma} + \frac{\sigma}{2}\right] \tag{1}$$

$$\varepsilon_{MGI} = -\frac{\pi[\ln(w/y)/\sigma - \sigma/2]}{(w/y)\pi[\ln(w/y)/\sigma + \sigma/2] - \pi[\ln(w/y)/\sigma - \sigma/2]} \tag{2}$$

In these equations, w is the minimum daily energy requirement (MDER), y is the average *per capita* DEC and σ is the standard deviation of the DEC distribution. The operators τ and π denote the standard normal probability density and cumulative distribution functions, respectively. We then calculate the malnutrition gap from the product of the minimum energy requirement and ratio of the malnutrition gap index and the malnutrition index. To compute the updated malnutrition headcount, we simply multiply the malnutrition index by the population headcount. To implement the model, we rely on the food security data published by FAO (2010, 2012). Detailed discussions on the methods used in creating the food security data for years 1991, 2001 and 2006 are included in the Supporting information (Data S2).

Selected food security data for 2006 are summarized in the second column of Table 1. In our reporting of nutritional outcomes, we only focus on key regions wherein chronic malnutrition is prevalent. These include the following: sub-Saharan Africa, Central Asia, China/Mongolia, Southeast Asia, South Asia, Central America and South America. Around 93 per cent of the world's undernourished live in these regions with almost 60 per cent residing in sub-Saharan Africa and South Asia. In these regions, roughly one out of five persons are malnourished. Looking at the malnutrition gaps, we see that the average depth of hunger in Central Asia, China/Mongolia, South Asia and Central America is greater than the world average.

3. Historical validation

We start our analysis by evaluating how well the model projects nutritional outcomes over the historical period 1991–2001 (10-years).[1] Often studies that use economic models to project future outcomes are not validated against history, making it difficult to assess what the model does well and what it does poorly. Furthermore, this historical assessment also provides a useful context for examining changes in the future. For this experiment, we implement shocks in population, *per capita* incomes and total factor productivity (TFP) growth in the crop, livestock and processed food sectors and these are listed in the Supporting information (Table S2 in Data S2). Note that drastic changes in *per capita* incomes occurred during this short-run period, and this will likely exaggerate changes in food consumption. To control for this, we imposed the regional demand responses calculated for the year 2001. Finally, we compare the simulated changes for the period 1991–2001 with the actual changes from published food security statistics from FAO (2012).

The results of the historical simulations are summarized in Figure 1. The top, middle and bottom panels of the figure report the average dietary energy intake, malnutrition incidence and gap, respectively. We observe that at the global level, SIMPLE broadly replicates the historical changes in average dietary intake, and malnutrition incidence and gap. However, results at the regional level are less satisfactory, which resonates with other studies seeking to validate global models. For example, in the comparison done by McCalla and Revoredo (2001), food balance projections from key international and national agencies were shown to become more prone to errors with greater levels of disaggregation. Even in developed countries wherein data are generally more accurate, there are discrepancies between actual and simulated changes, which the authors attribute to domestic policies. Baldos and Hertel (2013) validated the SIMPLE model over the period 1961 to 2006 and found that, while it did a good job at predicting changes in global production, the model failed to accurately capture the distribution of crop production across regions. They noted that the inconsistencies may have been driven by

[1] Our back-casting experiment is limited by the availability of historical data on nutritional outcomes which dates back to the period 1990–92.

Table 1 Selected food security statistics

Regions	Base data: 2006	Future scenarios: 2050			
		Baseline	Demand only	Climate change	
				No CO_2 fert.	CO_2 fert.
Average dietary energy consumption (kcal/capita/day)			In Δ relative to baseline		
World	2761	3413	−587	−51	83
sub-Saharan Africa	2110	2808	−478	−69	114
Central Asia	2546	4095	−748	−75	123
China/Mongolia	2989	4140	−907	−43	71
Southeast Asia	2562	3187	−568	−47	77
South Asia	2341	3513	−708	−74	120
Central America	2909	3453	−625	−30	48
South America	2903	3863	−824	−35	55
Malnutrition index (%)			In Δ relative to baseline		
World	12.0	1.9	6.0	0.3	−0.4
sub-Saharan Africa	23.5	2.4	9.9	0.7	−0.8
Central Asia	21.4	1.0	3.7	0.2	−0.2
China/Mongolia	9.6	0.9	5.0	0.1	−0.1
Southeast Asia	12.8	2.8	8.4	0.4	−0.5
South Asia	20.2	1.2	5.9	0.3	−0.3
Central America	10.1	3.6	8.1	0.2	−0.3
South America	8.2	0.9	5.2	0.1	−0.1
Malnutrition gap (kcal/capita/day)			In Δ relative to baseline		
World	235	168	34	1	−2
sub-Saharan Africa	207	137	40	4	−7
Central Asia	291	183	36	3	−4
China/Mongolia	250	184	47	2	−3
Southeast Asia	225	177	42	3	−4
South Asia	252	162	42	3	−5
Central America	252	215	44	2	−3
South America	221	167	44	1	−2
Malnutrition count (million)			In Δ relative to baseline		
World	764.2	176.9	552.5	27.0	−35.1
sub-Saharan Africa	157.7	46.5	193.1	13.4	−16.1
Central Asia	9.2	0.7	2.4	0.1	−0.2
China/Mongolia	127.6	12.3	69.9	1.2	−1.7
Southeast Asia	66.7	20.9	62.0	2.7	−3.7
South Asia	302.0	25.6	126.9	5.4	−6.9
Central America	19.0	9.8	22.0	0.6	−0.9
South America	30.8	4.5	26.1	0.4	−0.6

Source: Authors' calculations.

domestic agricultural policies, foreign trade agreements and other barriers to international trade.

In the case of malnutrition, there are some good reasons to expect such deviations at the regional level. In Central Asia, the dramatic transition from centralized to market economies has affected food security in the region. After dissolution of the Soviet Union in the early 1990s, the lack of access to inputs and weakened institutions have led to the severe disruptions in domestic

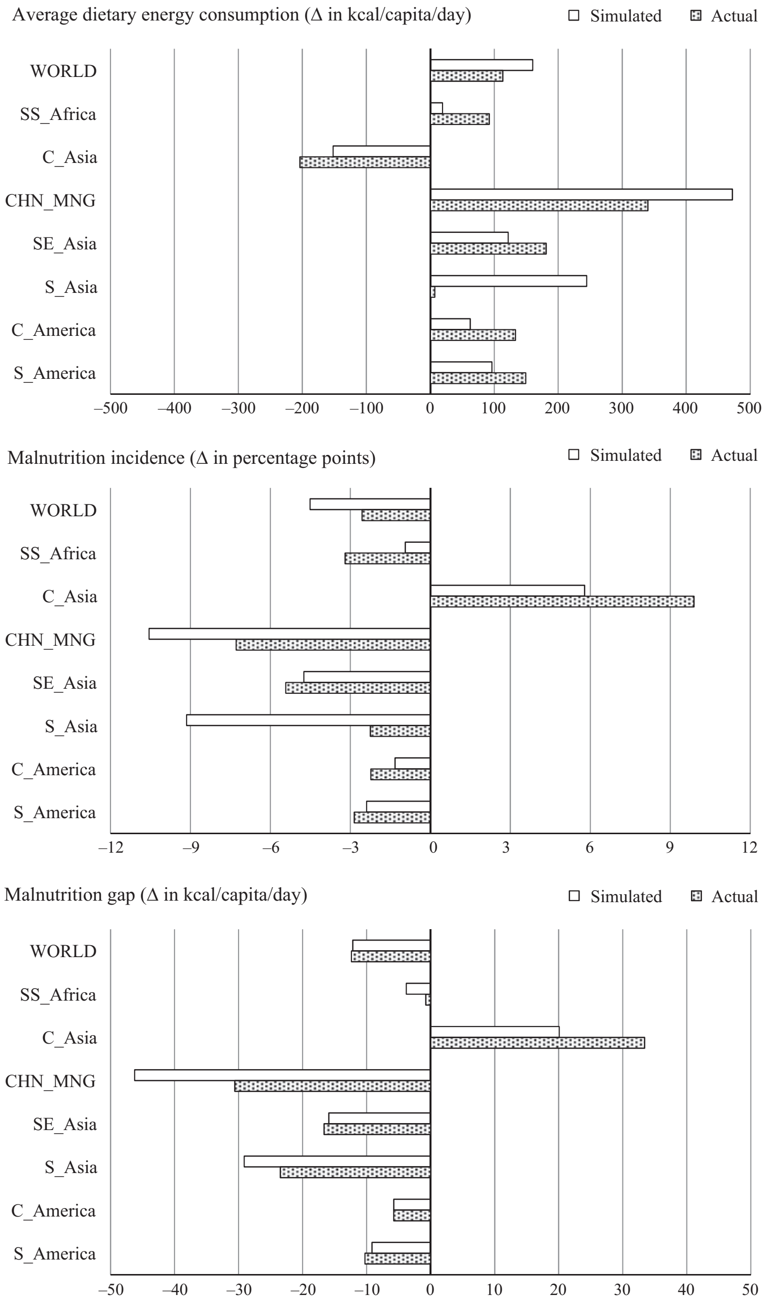

Figure 1 Selected food security statistics from 1991 to 2001: actual change vs. simulated change. Source: Authors' calculations.

agricultural production and distribution (Babu and Tashmatov 1999). Decreasing incomes coupled with higher food prices due to food shortages and rapid market liberalization have resulted in increased household expenditure on food, rising to levels observed in sub-Saharan Africa and South Asia

(Rokx *et al*. 2002). The persistence of malnutrition in India has continued to puzzle researchers. Deaton and Drèze (2009) report that caloric consumption in India has been declining despite improvements in rural and urban incomes, reductions in poverty rates and lower food prices. A closer look at the composition of food consumed shows that there seems to be a shift from cheaper to expensive sources of calories (e.g. from grains to meats and dairy) which may explain the reduction in overall calories (Sen 2005; Ray 2007).

4. Experimental design for future projections

Having tested the model against history, we now look into the future and implement a series of carefully designed scenarios to assess how global food security will be affected by population, *per capita* incomes, bioenergy policies, agricultural productivity and climate change. We begin with the baseline scenario for 2050 wherein we examine the impacts of population, *per capita* income growth, increased biofuel use and productivity improvements in the crop, livestock and processed food sectors. In SIMPLE, productivity improvements are primarily captured through growth in total factor productivity (TFP). Going forward to 2050, we assume that TFP growth in the crops sector is input neutral while for the livestock and processed food sector, TFP growth is input-biased (i.e. biased towards non-crop inputs). We then turn our attention to the drivers of food supply. We first explore the food security impacts of a stagnation in agricultural productivity ('Demand only' scenario). Specifically, we only apply the demand shocks outlined in the preceding scenario to highlight the importance of productivity growth in driving future nutritional outcomes. We then assess how global food security will be affected by climate change. Given the shocks in the baseline, we consider crop yield effects from climate change if there is no CO_2 fertilization ('No CO_2 fert.' scenario) and if there is CO_2 fertilization ('CO_2 fert.' scenario). These yield impacts are implemented as changes in TFP in the crops sector. Growth rates of each driver for the period 2006–2050 are listed in the Supporting information (Table S2 in Data S2). In the coming decades, we expect that population generally will slow down relative to *per capita* income, which highlights the growing importance of *per capita* income as a key driver of food demand especially in developing regions. Additional demand for crops will also come from steady biofuel use worldwide. On the other hand, there is great uncertainty in the future of agricultural productivity particularly in the crop sector. While TFP growth in this sector is expected to slow down globally, regional yield shocks suggest that crop production in developing regions, notably in South and South East Asia as well as sub-Saharan Africa, is quite vulnerable to climate change.

5. Results

All our projections regarding selected food security outcomes for the year 2050 are summarized under the "Future Scenarios: 2050" column in Table 1.

We begin with our baseline scenario for 2050 wherein we report the future values of selected food security outcomes when both demand and supply drivers are implemented. In the future, our baseline suggests that population and agricultural productivity growth will be slower than in the 10-year historical period, whereas global biofuel use and *per capita* incomes continue their steady rise. Our results show significant improvements in nutritional outcomes relative to 2006. Globally, average dietary energy intake increases by 24 per cent while the prevalence and average depth of malnutrition further decrease by 84 per cent and 29 per cent, respectively. Sharp rises in average DEC are observed in South Asia, China/Mongolia and Central Asia – regions with strong *per capita* income growth rates – while we see notable reductions in the incidence of malnutrition in sub-Saharan Africa, Central Asia and South Asia where malnutrition incidence falls sharply from at least 20 per cent in 2006 to < 3 per cent in 2050. Given these improvements, we see a significant reduction (around 77 per cent) in the global malnutrition count, which falls by 587 million between 2006 and 2050, despite increasing population. Most of these individuals who are lifted out of caloric malnutrition reside in South Asia, China/Mongolia and sub-Saharan Africa. However, we also observe that at both the global and regional level the percentage reductions in the prevalence of malnutrition are greater than in the malnutrition gap, highlighting the difficulty of reducing the average depth of malnutrition in the absence of improvements in the unequal distribution of DEC in these regions (Supporting information, column E in Data S4).

Figure 2 illustrates how the distribution of *per capita* dietary energy intake in a region shifts given the changes in average dietary energy consumption. Specifically, we compare the probability densities of *per capita* DEC in 2006 (solid line), obtained from published food security data (FAO 2010, 2012), and in 2050 (dashed line), based on our baseline scenario, for both South Asia and Australia/New Zealand. The vertical solid line within each distribution represents the minimum dietary energy requirement. The area to the left of this line is the fraction of the population that is malnourished, having dietary energy intake below the MDER. Note that the DEC distribution is much more compact for Australia/New Zealand than for South Asia, suggesting a more equitable distribution of dietary energy. Under this framework, as the distribution of dietary energy intake becomes more inequitable (i.e. greater standard deviation), at a given average DEC, the prevalence of malnutrition increases. Going forward in time, rising incomes lead to increased food consumption, and average dietary energy intake rises. This results in a thin tail to the left of the DEC distribution. The reduction in malnutrition incidence is then determined by the difference between the areas bounded by the minimum dietary energy requirement and the caloric distribution curves in 2006 and in 2050.

The changes in the composition of food consumed between 2006 and 2050 under the baseline scenario are reported in Figure 3. Globally, the volume of food consumption increases by about 31 per cent, most of which comes from increased consumption of livestock products and processed foods. Note that

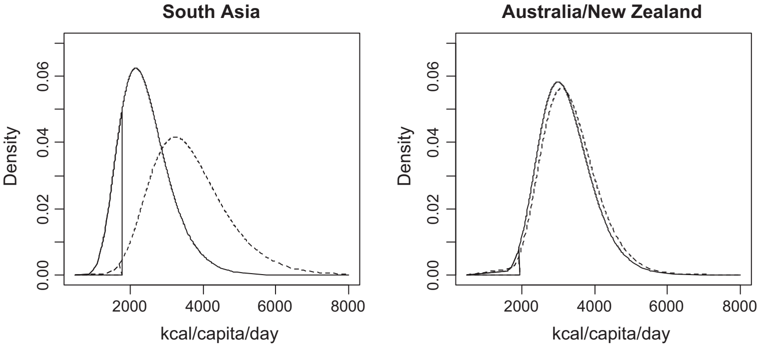

Figure 2 Probability densities of dietary energy consumption for South Asia and Australia/New Zealand regions in 2006 (solid line) and in 2050 (dashed line). Source: Authors' calculations.

food prices in all regions are declining in 2050 under this scenario (Supporting information, column A in Data S4), which suggest that agricultural productivity growth in the coming decades may exceed the growth in future food demand due to rising population and incomes. In regions with relatively low *per capita* incomes at present but facing strong income growth in the future, we observe larger increases in food consumption. These consist of Central Asia, sub-Saharan Africa and South Asia wherein food consumption increases by around 56 per cent to 75 per cent, nearly all of which comes from increased consumption of livestock commodities. Note that in SIMPLE, consumer responses to income and prices decline as *per capita* income rises, and it declines faster for crops relative to livestock and processed foods (Supporting information, column D in Data S4). Given this, additional income will be spent disproportionately on livestock and processed foods. The increase in food consumption is greater than the increase in average DEC. This is due to the changes in caloric content of food (Supporting information, column C in Data S4). Higher incomes facilitate quality upgrading, which may result in fewer calories per dollar spent on a given food type – as observed in crops and processed foods – as well as consumers' shift to a leaner and higher quality diet.

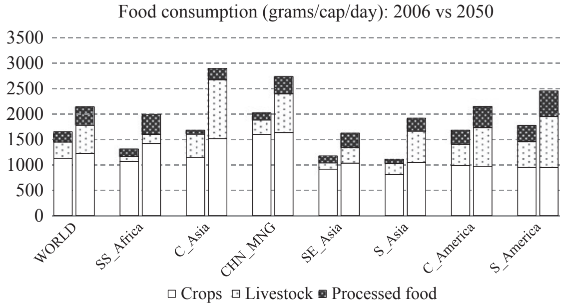

Figure 3 Composition of food consumption in 2006 and 2050. Source: Authors' calculations.

Returning to the scenarios reported in Table 1, we now consider the 'Demand only' scenario wherein the supply-side drivers are ignored. This allows us to isolate the impact of agricultural productivity growth on nutritional attainment. Note that the subsequent columns of Table 1 report the *differences* in food security outcomes relative to our baseline scenario in 2050. From this column of results, we see that improvements in nutritional outcomes are severely dampened if agricultural productivity stagnates. Note that without TFP growth, prices of all food aggregates will rise and even exceed price levels in 2006 (Supporting information, column A in Data S4). Rising food prices is detrimental to food consumption in developing regions as lower income consumers are relatively more responsive to price changes. With higher prices, the increase in commodity consumption due to higher income growth will be dampened (Supporting information, column B in Data S4). With only the demand drivers in place, the prevalence of malnutrition exceeds that in our baseline by more than four times (7.9 per cent vs. 1.9 per cent). Regions wherein the malnutrition incidence falls more slowly relative to the baseline include: sub-Saharan Africa, Central America and South East Asia. With rising incidence, the average depth of malnutrition in these regions also falls at a slower pace relative to the baseline. Under this scenario, the global malnutrition count between 2050 and 2006 declines slightly to 729 million people. However, across regions the increase in malnutrition count will be higher in the poorest countries, where the average caloric intake is low and the response to higher prices is most accentuated. Thus the malnutrition headcount in sub-Saharan Africa rises by 193 million, relative to the baseline. Under this (stagnant productivity) scenario, one-third of the world's malnourished may reside in sub-Saharan Africa by 2050. In sum, because of the high population growth in the coming decades, food security in this region is quite vulnerable to any setbacks in agricultural productivity growth. The results from the 'Demand only' scenario reaffirm the findings in the literature regarding the importance of productivity growth in agriculture and how these improvements strengthen food security, particularly in regions of the world wherein chronic malnutrition is prevalent (Nelson *et al.* 2010; Schneider *et al.* 2011).

We now look at the changes in nutritional outcomes in light of potential crop yield impacts of climate change in the presence or absence of CO_2 fertilization using the yield estimates from Müller *et al.* (2010). Rising CO_2 levels can directly benefit crop yields by stimulating photosynthesis and promoting water use efficiency for C3 crops such as wheat and rice (Long *et al.* 2004). Early estimates suggest that by the mid-century, the fertilization effect from boosted CO_2 levels in the atmosphere could increase average yields of C3 crops by around 13 per cent (Long *et al.* 2006). However, recent analysis at the grid-cell level shows that CO_2 impacts differ widely across crop types as well as agro-climatic conditions (McGrath and Lobell 2013). Moreover, CO_2 fertilization effects are quite uncertain as the variations in these impacts could be more than half of the variations from temperature and precipitation (Lobell and Gourdji 2012). These findings suggest that there is great uncertainty on how CO_2 fertilization will affect crop yields in the future, and we should keep this in mind as we look at the nutritional outcomes in 2050 when climate change is considered. Thus, we begin with a scenario in which these effects are omitted.

Without CO_2 fertilization ('No CO_2 fert.'), crop yields in most regions will be adversely affected by the temperature and precipitation impacts from climate change. Globally, yields will decline by around 1.3 per cent per decade under this scenario, which is close to the expected reduction (1.5 per cent per decade) in the literature (Lobell and Gourdji 2012). With relatively lower crop yields under this scenario, the reduction in crop prices from projected crop TFP growth will be slightly dampened. At a glance, we see that the gains in food security from 2006 to 2050 are reduced relative to our baseline scenario. At both global and regional levels, the change in average DEC increases and average depth of malnutrition are negligible. However, the *relative* reduction in average DEC is greater (at least 35 per cent more than the global reduction) in sub-Saharan Africa and South Asia wherein consumers are more responsive to food prices. The gravity of climate change impacts on food security is quite evident if we look at the prevalence of malnutrition. At the global level, malnutrition incidence increases by about 16 per cent relative to the baseline scenario. Across regions, the increase in the prevalence of malnutrition is more than 20 per cent in sub-Saharan Africa and South Asia. Coupled with the steady growth in population, global malnutrition count actually increases under this scenario (by about 27 million, relative to the baseline) and most reside in sub-Saharan Africa and South Asia.

When the effects of CO_2 fertilization are added in ('CO_2 fert.'), crop yields are higher in most regions of the world (by 2.2 per cent per decade globally), resulting in slightly lower crop prices and further improvements in food security outcomes particularly for the poorest regions of the world. However, similar to the previous case, we do not observe these gains explicitly if we look directly at the average DECs but relative to the increase in the global average, we see stronger gains (by more than 37 per cent) in average dietary energy intake in sub-Saharan Africa, Central Asia and South Asia. With CO_2 fertilization in place, the global malnutrition incidence further declines by 20 per cent relative to our baseline. Regions which benefit most from reduced malnutrition headcount under this scenario are sub-Saharan Africa, South East Asia and South Asia. With CO_2 fertilization effects, the number of malnourished persons globally further declines by around 35 million relative to the baseline.

The results from the previous scenarios illustrate the uncertainty posed by climate change on global food security as it may enhance or dampen improvements in nutritional outcomes in the future depending on the strength of the yield impacts of CO_2 fertilization. More importantly, these impacts are further magnified in lower income regions wherein consumers are more responsive to changes in food prices. Furthermore, these results highlight the importance of looking at nutritional outcomes that incorporate the distribution of caloric energy across world region. If we look only at the average dietary energy consumption, we barely see the difference between our baseline and the scenarios with climate change yield impacts. However, as evidenced by the changes in the prevalence and headcount of malnutrition, we see that climate change could have significant implications on the nutritional outcomes of millions of people, particularly for those living in hunger-stricken regions of the world.

To better understand how each driver affects past and future food security outcomes, we evaluate the contribution of each of the exogenous drivers (Supporting information, Data S3) to the simulated changes in the malnutrition count for the historical period 1991–2001 (top panel) and for the 'Climate Change no CO_2 fert.' Scenario (bottom panel) in Table 2. The second column of Table 2 shows the total change in the malnutrition count while the rest of the columns summarize the contribution of each driver to the total change. Rather than reporting the resultant changes in malnutrition count directly, we report the individual impacts of *per capita* incomes, biofuel use, TFP and climate change relative to the impact of population to facilitate comparison of their relative importance. Starting with the historical period, population growth alone contributed to an increase in the global malnutrition count by 266 million persons. Note that this contribution is large as we are starting at a larger base of malnutrition headcount in 1991 (around 833 million). The impacts of income and TFP growth on the world malnutrition headcount over this historical period are around 47 per cent and 109 per cent as large as the population impact and opposite in sign, respectively. As a consequence of income and TFP growth, malnutrition count fell over this short-term period. In most regions, the primary force in reducing malnutrition headcount is TFP. For China/Mongolia, *per capita* income is the main driver of lower malnutrition count.

Next, we decompose the results of the longer and forward-looking 'No CO_2 fert.' scenario (bottom panel of Table 2). We see that population growth, increased biofuel use and climate change all contribute to greater food insecurity at the global level while growth in *per capita* incomes and TFP improve nutritional outcomes. The individual impact of population on the global malnutrition count is 277 million which is close to the historical impact – although the future period is more than four times as long. This is mainly due to a smaller base of malnutrition headcount in 2006 (around 764 million) and the sharp slowdown in expected population growth over this future period. At the regional level, we see the growing importance of population as a driver of malnutrition count in sub-Saharan Africa, South Asia and South East Asia – regions with steady population growth rates in the coming decades (Supporting information, Table S2 in Data S2). We also report the individual impacts of rising *per capita* incomes, increased biofuel use, TFP growth and climate change yield effects. As with the historical analysis, we express these relative to the contribution of population growth. At the global level, the reduction in malnutrition headcount will be mainly driven by TFP growth followed by *per capita* income growth. Projections for South Asia and China/Mongolia suggest that *per capita* income will be the key driver. However, in light of the historical puzzle of reduced caloric consumption, despite rising incomes in South Asia, some caution should be attached to this finding.

Examining the relative impacts of increased biofuel use and climate change yield effects, we observe that their contribution is far less than that of population, income or TFP. Given the assumed growth rates in our future experiments (Supporting information, Table S2 in Data S2), increased biofuel use is the least important driver of food security in the coming decades. It has roughly 6 per cent of the contribution of population growth on global malnutrition count. Climate change in the case of no CO_2 fertilization has a greater impact than increased biofuel use. Globally, the contribution of this characterization of climate change is around 16 per cent of the contribution of population on the changes in the malnutrition count, respectively. This is consistent with the assessment of Schmidhuber and Tubiello (2007) regarding the food security impacts of climate change. The authors reviewed the literature and noted that the potential impact of climate change on the headcount of people at risk of hunger is relatively smaller than the impact of socio-economic drivers such as population and *per capita* incomes. However, as revealed in our analysis, climate change could still pose significant risk on the food security of people residing in the poorest regions wherein chronic malnutrition in persistent.

Table 2 Contribution of selected drivers on malnutrition count

Regions	Total change	Contribution of population	Contribution relative to population (Index = 100)			
			Per capita income	Biofuels	TFP	Climate change: No CO_2 fert.
Malnutrition count (millions)						
Historical experiment: 1991–2001						
World	−150.7	266.5	−47	–	−109	–
sub-Saharan Africa	44.6	73.7	25	–	−64	–
Central Asia	3.6	2.9	135	–	−112	–
China/Mongolia	−117.7	40.8	< −200	–	−149	–
Southeast Asia	−7.8	28.5	−18	–	−110	–
South Asia	−74.0	93.9	−63	–	−116	–
Central America	1.2	5.2	16	–	−94	–
South America	−1.7	10.6	5	–	−121	–
Climate change no CO_2 fert.: 2006–2050						
World	−560.0	276.6	−159	6	−166	16
sub-Saharan Africa	−97.8	145.0	−91	5	−94	13
Central Asia	−8.4	1.9	< −200	7	−171	17
China/Mongolia	−114.0	10.0	< −200	15	< −200	35
Southeast Asia	−43.2	22.9	−104	7	< −200	18
South Asia	−271.0	64.2	< −200	9	< −200	21
Central America	−8.6	7.0	−14	4	< −200	11
South America	−25.8	6.3	−156	6	< −200	16

Source: Authors' calculations.

6. Summary and conclusion

In this paper, we explore how global food security will be affected in 2050 given the projected trends in the underlying drivers of the world farm and food system. We used the SIMPLE model and introduced a food security module to calculate the headcount, prevalence and average depth of malnutrition and to assess the contribution of these drivers on nutritional outcomes. To evaluate the model, we conducted an historical experiment from 1991 to 2001, based on historical growth rates in population, *per capita* incomes and TFP. The results indicate that at the global level, we closely replicate the observed increase in the average dietary energy intake while also doing a reasonable job capturing reductions in the malnutrition incidence and gap, respectively. Turning to the regional level, model performance is less satisfactory. Accurately predicting changes in regional malnutrition – particularly in South Asia – have posed a major challenge in the literature and the SIMPLE model is not immune to this problem.

Looking ahead from 2006 to 2050, we account for projected growth in population, *per capita* incomes, biofuel use and TFP. We also consider the implications of climate change in our analysis. In the future, population growth is projected to slowdown while biofuel use, *per capita* incomes and agricultural productivity are expected rise steadily. The net effect of these diverse drivers is to reduce the global malnutrition incidence, count and gap particularly in the poorest regions of the world. When TFP growth is removed from the picture, nutritional outcomes worsen, with significantly less reduction in the global headcount over the 2006–2050 period. This highlights the importance of increasing productivity growth in agriculture to improve food security outcomes in the coming decades. The impact of climate change on future nutritional outcomes is uncertain. Depending on the strength of the yield impacts of CO_2 fertilization, climate change may strengthen or weaken the future gains in global food security. Overall, the results from these scenarios illustrate the importance of looking at nutritional outcomes based on distribution of caloric consumption as changes in the average dietary energy consumption under climate change are negligible, while changes in malnutrition prevalence and headcount are substantial.

Our analysis of the individual drivers of global food security shows that from 1991 to 2001, population and TFP were the dominant drivers of malnutrition count. At the global level, the impact of population on malnutrition headcount exceeds that of *per capita* income. Going forward to 2050, the relative impact of population on malnutrition count will be offset by the relative contribution of *per capita* income and TFP growth. On average, the contribution of biofuels and climate change are far lower than that of the other drivers. These results suggest that future nutritional outcomes will be mainly affected by socio-economic conditions as well as productivity trends in the agricultural sector. However, climate change will still be a relevant driver of nutritional outcomes especially for those residing in regions of the world where chronic malnutrition is prevalent.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Overview of the SIMPLE model.

Data S2. Description of database and growth rate assumptions.

Data S3. Model implementation.

Data S4. Selected statistics on food demand and food prices.