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The effect of bigger human bodies on future global calorie requirements

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The effect of bigger human bodies on future global calorie requirements

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Abstract

Global food demand will see a rapid increase over the coming decades. Existing studies on future calorie demand consider mainly population growth and rising incomes. We add to the literature by estimating the effect of increases in human weight caused by rising BMI and height on future calorie requirements. We produce projections that are solely based on human energy requirements for maintenance of weight. We develop four different scenarios that affect this value and show that increases in human height and BMI could lead to an increase in global calorie requirements by 18.73 percentage points between 2010 and 2100 compared to a world where the weight per age-sex group would stay the same. These increases will particularly affect countries which are already facing higher rises in calorie requirements due to high population growth. The region most affected by this pattern is Sub-Saharan Africa.

Keywords: World food demand, nutrition, global outlook, agricultural outlook.

JEL Classification: O13, J11, Q01, Q11

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1 Introduction

The growing demand for agricultural products is a well discussed and important topic. According to Alexandratos and Bruinsma (2012) world agricultural production needs to increase on average by 1.1 percent per year between 2005/7 and 2050 to meet the increasing demand. These numbers are primarily based on projections based on population growth, increasing incomes and associated changes in food demand (e.g. rising meat consumption), as well as a limited expansion in the usage of biofuels. Yet, the demand for food cannot only be seen as the result of what a person can afford to eat but also as what a person needs to eat from a nutritional point of view.

Walpole *et al.* (2012) take the latter perspective on this issue. They consider the biological fact that a person with a higher weight will need more energy to sustain her body functions. Quantifying this aspect on a global level they show that a higher average weight in a population will imply a sizable increase in the nutritional energy the population would need to consume. They estimate that if adults in all countries had the same age-sex BMI (body mass index, defined as body weight in kilograms divided by the squared body height in meters) distribution as the US population, the increase in energy requirements would be comparable to the requirements of 473 million adults of global average BMI in 2005.

We build on the assessment of Walpole *et al.* (2012) to estimate future nutritional energy requirements (in the following also referred to as calorie requirements), thereby creating an alternative approach to estimate future requirements for calorie supply. We do not intend to challenge the estimates by Alexandratos and Bruinsma (2012), but rather complement them. While they estimate future demands based on economic possibilities of the population, our estimates show what people would need to eat if not facing economic restrictions (i.e. the calories required to keep body weights). We do not estimate what would be necessary to supply enough calories to every person to reach a healthy weight. Instead we take into account an existing trend towards higher weight, which in many countries has moved far beyond a healthy weight. This trend is driven by two factors, increasing height (as observed over the last century by NCD Risk Factor Collaboration (2016a)) and a trend towards higher average weight at a given height, expressed in terms of the average BMI (as estimated for the last decades by NCD Risk Factor Collaboration (2016b)). We limit our estimation to calories as we can build on a literature that shows a clear relation between body weight and calorie requirements. For other macro and micro nutrients such models are not directly available, predictions would require an increasingly complex estimation, and stronger assumptions would need to be taken to deal with complex interdependencies.

We first present our data sources and the methodology to estimate the average calorie requirement in a population. In Section 4 we introduce the scenarios we use to exemplify the effect of growing height and BMI on global requirements. In chapter five we present the results of these estimations. Our results show an increase in global calorie requirements by 18.73 percentage points between 2010 and 2100 compared to a world where the weight per age-sex group would stay the same. This amount of calories relates to the requirements of India and Nigeria in 2010 combined. The increases will particularly affect countries which are already facing higher increases in calorie requirements due to high population growth. The region most affected by this pattern is Sub-Saharan Africa. We close by giving a short discussion of the results and their implications.

2 Estimation of 2010 human weight data

2.1 Data sources

Currently, no representative measure of human weight is available on a global level. For this reason, we have to backward estimate it from the available information and estimates on human height and BMI. Doing this, we combine a set of data sources.

Information on average BMI by age-sex group was kindly provided by NCD Risk Factor Collaboration relating to research published by NCD Risk Factor Collaboration (2016b).[1] Regarding height, for persons

[1] For data on Algeria and Niger we made a small adjustment by assuming that the BMI of women over 85 years of age is the same as the one of women aged 80 to 84. We did this as the value for 85 year old women had

under the age of 20 years we used data that was kindly made available by the FAO statistics division and which is mainly based on DHS surveys, James and Schofield (1990), and different national surveys. Height for older age groups was calculated from NCD Risk Factor Collaboration (2016a) with the help of a linear rate of height reduction in the population over age, which NCD Risk Factor Collaboration kindly provided. The combination of the data is necessary as both sources have some disadvantage for our purpose. NCD Risk Factor Collaboration (2016a) does not provide height data for age groups under 20 years while the data provided by FAO does not differentiate among the height of older age-groups. The latter causes problems as forecasts expect the number of older age groups to increase strongly and we therefore need to take into account height reductions in old age.

As we had height data for fewer countries than BMI data, we replaced the missing height data with that from countries which seem reasonably close in geographic and economic distance. The replacements are listed in Table 5.

To estimate weight, which rises non-linearly with height at a given BMI, we need to take into account the variance of height in the population. Data on variance in height by age-sex group was not readily available. We estimated it using data from the IFLS 5 survey on Indonesia (Strauss *et al.*, 2016). We chose the survey as we considered Indonesia as an emerging middle income country with a large population to be relatively good approximation of the average world population, while in the same time high quality data for human height is available for the country. In contrast to many other surveys the IFLS 5 comprises data on a comparably large population of elderly people, which is beneficial given the aging world-population in our calculations. For comparison we also calculated the same data for the United States based on the NHANES 2009-2010 survey (Centers for Disease Control and Prevention (CDC)/National Center for Health Statistics, 2013). Averaging the difference over age groups up to age 80 the variance in heights is 0.07 cm^2 higher for men and 0.14 cm^2 higher for women in Indonesia compared to the United States. At these levels the differences would not have a sizable effect on our results. For the group over age 80 the difference is considerably higher but this is likely to be due to the limited sample sizes.

Data on future demographics are taken from the medium variant of United Nations, Department of Economic and Social Affairs, Population Division (2015). This source provides population per five-year-age-sex group estimates up to the year 2100 for countries as well as dependent territories. As we do not have BMI and height data for all these areas we merged dependent territories into the respective independent states. For some other countries we applied data of geographically, economically or historically close countries. We list these cases in Table 6.

2.2 Weight of adults

Estimation of human weight for adults is based on the backward estimation of average weight in an age-sex group from average height in meters and average BMI in kg/m^2. This estimation was derived by Walpole *et al.* (2012). Their derivation of the average weight in an age-sex group W takes into account that in a population each individual deviates from the average with regard to their BMI and height. So they define the difference between average BMI ($\overline{BMI}$) and individual BMI (BMI) as $b = (BMI - \overline{BMI})$. Equivalently they define the difference between average height ($\overline{H}$) and individual height (H) as $h = (H - \overline{H})$. Therefore a group of individuals' expected weight $E(W)$ can be estimated by:

$$\begin{aligned} E(W) &= E(BMI * H^2) = E((\overline{BMI} + b) * (\overline{H} + h)^2) \\ &= E((\overline{BMI} + b) * (\overline{H}^2 + h^2 + 2\overline{H}h)) \\ &= E(\overline{H}^2\overline{BMI} + h^2\overline{BMI} + 2\overline{H}h\overline{BMI} + \overline{H}^2 b + h^2 b + 2\overline{H}^2 hb) \\ &= \overline{H}^2\overline{BMI} + E(h^2)\overline{BMI} + E(h)2\overline{H}\overline{BMI} + E(b)\overline{H}^2 + E(bh^2) + E(hb)2\overline{H} \\ &= \overline{H}^2\overline{BMI} + E(h^2)\overline{BMI} + E(bh^2) + E(hb)2\overline{H} \end{aligned} \tag{1}$$

extremely large confidence intervals and the point estimate were at 16.73 in Niger and at 13.59 in Algeria, which we deemed to be unrealistically low.

As data on several of these terms is limited we have to make a set of assumptions. Like Walpole *et al.* (2012) we assume that height and BMI are independent and the variance of height over all values of BMI is constant.[2] Under these assumptions the formula becomes:

$$E(W) = \overline{BMI} * (\overline{H}^2 + V(H)) \tag{2}$$

As we do not have data on variance in height, $V(H)$, per age-sex group for every country, we use the estimate derived for Indonesia as a general approximation. As described, the estimates for this value are not differing much between the United States and Indonesia. Considering the difference in the 2010 average BMI levels between the United States (24.79 for women and 25.43 for men) and Indonesia (21.06 for women and 20.53 for men), also the assumption that the variance in height is constant over BMI does not seem to introduce sizable biases. In fact, the difference in average variance in women's height between the United States and Indonesia of 0.0007 m^2 among women under 80 years of age corresponds to a 5.25 g difference in weight for a population with an average BMI of 25 kg/m^2. For men the difference corresponds to only 1.75 g. The differences are substantially larger amongst persons over 80, driving the estimated differences at BMI 25 kg/m^2 to 550 g for women and 850 g for men. However, this is little surprising given the larger variance in age in this group in the United States population, caused by the higher life expectancy.

Based on data availability, our age groups are divided by five year steps where for ages over 80 we have to fall back to information on younger cohorts or use aggregated estimates for 80 and above. For ages 100 and higher also population estimates are not separated in 5-year groups.

As a quality and robustness check of these assumptions, we use direct information on weight gathered in Demographic and Health Surveys (DHS). We use the newest DHS data available in each of the age groups 20 to 29, 30 to 39, and 40 to 49 and compare it to the population averaged weight we estimated for these age groups. For women we can compare the values in 56 countries. Averaging over all countries and taking into account the relative population of each group, we overestimate weight by 122 g. In this number over and underestimations cancel each other out, though. I.e. underestimations in some countries are balanced out by overestimations in others. The mean of absolute values per country does not suffer from this problem and also this is only 845 g. The largest difference we observe is 2.59 kg. For men we can only compare the values in 17 countries. On average, we underestimate male weight by 96 g with the average deviation from the measured value being 665 g. Therefore, while there are some discrepancies there is no strong deviation of the estimates in one direction: While we slightly overestimate weight in women, we slightly underestimate weight in men in the countries where we have direct observations at our disposal.

2.3 Weight of children and adolescents

The weight of children below five years of age is based on the FAO weight for length/height tables (de Onis *et al.*, 2007) in combination with data on human height/length. We assume that the average weight in each age-sex group equals the weight of the reference population. This simplification ignores existing over- and underweight in children. The assumption has the advantage that we rule out that growth in height is inhibited by childrens underweight. This is necessary for scenarios in which we assume an increase in average height to be realistic. As underweight in children is more likely due to stunting and not wasting (Uauy *et al.*, 2008), the bias due to overestimation of weights in childhood is likely to be small. Therefore, overestimations of child weight in underweight populations will only partially balance out underestimations of weight in overweight populations. Hence, we are likely to systematically underestimate weight in children.

[2]We test these assumptions using data on the population aged 20 to 79 years from the IFLS 5 survey on Indonesia (Strauss *et al.*, 2016). Both assumptions are violated by the data but this is of little practical importance. Against the assumption that height and BMI are independent, both are significantly correlated on the 1 percent level. The correlation between BMI and variance in height is significant only amongst women. With a correlation of $r = -0.1377$ this is also the largest value. In the given dataset the excluded terms $(E(bh^2) + E(hb)2\overline{H})$ correspond to a underestimation of the weight by 4 g over the entire population. Looking at it by sex-age groups, the largest underestimation equals 122 g, while in 21 of the 24 groups the value stays below 100 g. Therefore, excluding the respective terms from the calculation, does not have a large effect.

We follow the same method for the estimation of children aged five to 18. For this age group the reference standards are defined in terms of BMI and we take the reference BMI as the average BMI in our population. Like in the older age groups we use height and variance in height to deduct the average weight from the BMI value. As with the younger children, this is likely to lead to a net underestimation of the weight of adolescents and thus will lower our resulting calorie requirements.

Like we did for adults, we control the quality of our data by comparing it to DHS data at our disposal.[3] Doing this we create simple weight averages for the age groups 0 to 4, 5 to 9, and 10 to 19 years from the estimates which are available for each year of age. As we do not have information on the number of persons for every year of age we cannot construct a population averaged measure. Therefore, we ignore mortality and the potentially larger number of births in younger cohorts related to the form of the age distribution in most countries. This introduces an upwards bias into our results (as without weighting we imply that there are as many older as younger children in each age group). The comparison shows that our estimates for the age group 0 to 4 years is very close to the measured data. We underestimate the weight of girls by 213 g and that of boys by 142 g (with an average deviation from the real value being 510 g and 471 g respectively). For the group aged 5 to 9 years we overestimate the measured weight in all countries. On average girls are 5.05 kg heavier and boys 6.1 kg (with average deviations being identical). In the group aged 10 to 19 years we underestimate the weight of women in all and that of men in 17 out of 19 countries. On average we underestimate girls weight by 8.08 kg and that of boys by 4.6 kg. Yet, over all large parts of the differences cancel out when we look at the population weighted average over the three age groups. In the 53 countries for which we have data for girls in all three age groups we underestimate girls weight by on average 2.25 kg. In the 17 countries with data for boys we overestimate their weight on average by just 279 g.

3 Estimation of calorie requirements

Our estimations of the average calorie requirements are based on FAO/WHO/UNU (2004). According to this report, the energy needed by an adult can be estimated given the persons sex, age, weight and activity level. The first three factors define the basic metabolic rate of a person (BMR). This is the energy required by a person that is awake, in a supine position, did not eat for ten to 12 hours, physically rested in the eight hours before, is mentally relaxed, and is in an environment where she neither needs to generate body heat nor need to cool down the body temperature. We present these values in Table 1.

Table 1: Equations for the estimation of BMR from body weight

Age *Years*	Males *BMR: kcal/day*	Females *BMR: kcal/day*
18-30	$15.057 * kg + 692.2$	$14.818 * kg + 486.6$
30-60	$11.472 * kg + 873.1$	$8.126 * kg + 845.6$
≥ 60	$11.711 * kg + 587.7$	$9.082 * kg + 658.5$

Source: FAO/WHO/UNU (2004).

The physical activity level (PAL) works as a multiplier of the BMR. We assume that on average people follow a moderately active lifestyle and use the lowest multiplier connected to this group in the frame work of FAO/WHO/UNU (2004), which is 1.7. We thereby decide for a higher PAL than is being used by the FAO in estimations of food insufficiency, which is 1.55 (FAO Agriculture and Economic Development Analysis Division, 2015). This difference is due to the different goals of the estimations. While FAO Agriculture and Economic Development Analysis Division (2015) estimate the minimum

[3] We can compare the weight of children aged 0 to 4 years in 56 countries, that of those aged 5 to 9 years in 53 countries for girls and 52 for boys, and that of the 10 to 19 year old in 56 countries for girls and in 19 countries for boys.

necessary for good health order, we estimate what is most likely metabolized in everyday life. I.e. the lower PAL is chosen by the FAO to relate to the minimum level under which healthy body functions cannot be sustained. Our estimates are not supposed to relate to the lower bound but to the likely average requirements of a population. Notice that as the PAL acts as a multiplier, increases in the BMR due to higher body weight will have a more than proportional effect on the calorie requirement.

Importantly, the values we estimate in this fashion are not the energy required for a persons healthy living but the energy to maintain a persons given weight. For healthy living it would be sufficient to provide the energy required at the lowest healthy BMI level. Our estimate instead gives the energy required to keep the given weight. As a simplification, we do not take into account the energy required to build up the additional weight. Ignoring the net energy requirement of this process introduces an underestimation in our estimations, yet we are optimistic that this effect is comparably small.

The daily calorie requirements of children above one year are based on the parameters of a quadratic regression of weight on children's total energy expenditure and an increment for the energy required for growth (FAO/WHO/UNU, 2004). Denoting the calories used for growth as ι_f for girls and ι_m for boys, this formula is given for girls as

$$kcal/day_f = 263.4 + 65.3 * kg - 0.454 * kg^2 + \iota_f \tag{3}$$

and for boys as

$$kcal/day_m = 310.2 + 63.3 * kg - 0.263 * kg^2 + \iota_m. \tag{4}$$

These estimations already account for energy spend on activities.

For children not older then 12 months we use another estimate by (FAO/WHO/UNU, 2004), specifying the calorie requirements as

$$kcal/day = -95.4 + 88.3 * kg + \iota_i. \tag{5}$$

Also here ι_i defines the increment for growth, but there is no differentiation between boys and girls requirements. As we also include the energy requirements for lactation, we only estimate the energy necessary in the seventh to 12th month. Accordingly, the increment for growth is the average requirement over the respective month. As we do not have height data per month, we have to use the average height of all infants, thereby including the height of those six month and younger. Thereby, we underestimate the actual height of the seven to 12 month olds, which again leads to an underestimation of calorie requirements in this age group. This bias is (partially) reduced by a second bias: As we only have data on the total population aged zero to four years, we assume that the population is evenly distributed over age in this group. This is most likely not the case as due to child mortality the number of children reduces over age and in a growing population younger cohorts are larger. Hence, we underestimate the share of below one year olds among the population of the zero to four years old.

We account for the energy required due to pregnancy and lactation of mothers by multiplying the number of births in each year with the energy requirement for both. In doing this we use energy requirements from (FAO/WHO/UNU, 2004). We assume 6 months of exclusive breastfeeding and ignore miscarriages.

To derive the yearly calories required in a country we multiply the estimates with the population in each age-sex group, aggregate over all age-sex groups and multiply by 365. As the numbers we estimate in this way are large, we state them in tera calories (i.e. calories multiplied by 10^{12} or kcal multiplied by 10^9) on the country level and in exa calories (i.e. calories multiplied by 10^{15} or kcal multiplied by 10^{12}) on the global level.

4 Scenarios of future height and BMI

We design four scenarios to illustrate the influence of population growth, and increases in average BMI and height. We simplify by assuming that these changes do not affect the demographic development, though we would expect that a connection exists (e.g. as excessive BMI correlates with increased mortality and taller height correlates with lower mortality).

4.1 Scenario 1: Population increase and stable weight

In this scenario we keep the average weight per age-sex group stable and assume that the development of the world population between 2010 and 2100 will follow the medium variant of the 2015 Revision of the UN World Population Prospects. In our framework the demographic development can affect national calorie requirements not only due to a simple increase in the number of people. Changes in the balance between men and women are meaningful as in a given age group women are on average smaller and at a given weight their calorie requirements are below men's. Despite having an on average higher BMI (NCD Risk Factor Collaboration, 2016b) women therefore need on average less energy. The only exception to this rule is the group aged over 85 years in Timor-Leste.

Changes in the age composition of countries are meaningful as weight, height and calorie requirements in a population differ over age groups. Overall, energy requirements by age follow an inverted-U-shaped function.

Lastly, the importance of a country's average calorie requirement increases with the share of the world population it hosts. While the importance of countries with low or even negative population growth (e.g. China, Germany, and Russia) declines, the importance of countries with high growth rates increases. Particularly, in the given estimations the importance of Sub-Saharan countries' average calorie requirements moves into the focus.

We use the same demographic development as the basis for all other scenarios.

4.2 Scenario 2: Increase in BMI

In this scenario we illustrate the potential influence of an increase in the average BMI in each country's population. Between 1975 and 2014 global average BMI was estimated to have increased by 2.5 kg/m^2 in men and 2.3 kg/m^2 in women and the trend between 2000 and 2014 does not indicate that this development will stop in the near future (NCD Risk Factor Collaboration, 2016b). Increases in BMI are inducing higher weight at a given height, thereby increasing calorie requirements.

In our estimation we assume that all countries will experience an increase in average BMI of men and women as it was estimated for the Mexican population between 1975 and 2014 (NCD Risk Factor Collaboration, 2016b). We choose Mexico as it is an Upper-Middle-Income country with a large population that saw a strong increase in both male and female average BMI. Some smaller countries (Equatorial Guinea, Saint Lucia, Samoa) saw larger increases in the time between 1975 and 2014 but to ensure representativity concerns we decided for a country with a considerably larger population. Over the described time span, the male BMI increased on average by 0.37 percent each year. In 2014 Mexican men's average BMI reached 27.47 kg/m^2. Women experienced on average a growth rate of 0.57 percent per year, reaching 28.6 kg/m^2 in 2014. These numbers relate to the WHO reference population and therefore are not affected by changes in the demographic composition. The Mexican BMI levels in 2014 are surpassed by other countries. For men the highest BMI was estimated for American Samoa (32.18 kg/m^2) with Mexico having the 29th highest BMI out of 186 countries. American Samoa was also estimated to have the population with the highest BMI among women in 2014 (34.83 kg/m^2) and Mexico follows on the 37th place, just after the estimate for the United States. Therefore, Mexico is an example of a country with high BMI levels but far from being an outlier. And note that we only assume that countries will reach Mexicos level in 2010, but it could well be that the increases in BMI in these countries (as well as in Mexico) rise beyond the level of Mexico in 2010. So while we model substantially rising BMI, the increase could actually be larger.

Specifically, in our model countries with an average BMI below Mexican levels will increase their BMI at the average Mexican yearly rate observed between 1975 and 2014 until they reach the Mexican level. Where the average BMI is above this level we model a decrease at the same rate (the latter being an optimistic assumption on countries ability to fight overweight and obesity). At these growth rates all age-sex groups in all countries have the same average BMI as Mexico did in 2010 by 2100.

Comparing the modeled BMI changes with historical data shows that the average increase over decades is rather conservative but in a reasonable range. To compare our scenario with the historical findings we calculate the global average BMI per age-sex group and calculate the age-standardized average for the world population over age 18. The age adjustment uses the WHO standard (Ahmad *et al.*, 2001). The average change per decade is 0.36 kg/m^2 for men and 0.44 kg/m^2 for women. Based on our model, increases are much larger in the first decades than in the second half of the century, when more and more countries reach the maximum BMI. For the years from 1975 to 2014 NCD Risk Factor Collaboration (2016b) estimate an average increase by 0.63 kg/m^2 per decade for men and 0.59 kg/m^2 for women. The historical data show higher growth rates but it is unclear if those rates could realistically continue over more than twice the time in the future. Hence, our more conservative estimation method seems preferable.

4.3 Scenario 3: Increase in height

Another factor increasing weight and thereby the calorie requirements is an increase in the average height per person. Conditional on the health of mothers and children, this is a likely scenario which was observed over the last century in a number of countries. We choose the country with the tallest height reached - the Netherlands - as an example in this case.[4] As we have data for a sufficiently large number of years and as our own estimates relate to the development over the 90 years between 2010 and 2100, we use the average increase in height per year between 1907 and 1996 in both sexes to model changes in this scenario. The average yearly increase was estimated to be 0.079 percent in Dutch women and 0.071 percent in Dutch men. For simplification, we assume that the average height in each age between zero and 19 years increases by this factor. Therefore, growth takes place only up to age 20 in our model. Furthermore, we assume that average height does not grow beyond Dutch levels measured in 2010.

As human height starts reducing in later life years we use the same factor of height reduction in age we used to calculate height per age group. Comparing this factor with evidence from the Baltimore Longitudinal Study of Aging (Sorkin *et al.*, 1999) we find comparable reductions in height, thereby supporting our strategy. We prefer our method over using the factor from the latter study, as it does not take into account the higher mortality of smaller persons while this influence is included in the estimate of the NCD Risc Consortium.

We model a process in which age is inherited by the next older group after five years and the reduction in height due to five years of aging is then deducted for all age groups over 19 years. The exception is the group of 20 to 24 year olds. As the aging factor that was provided applies for all people above age 18, persons in the age group 20 to 24 did only experience this effect for on average 3 years.

Using this method height converges towards Dutch levels by 2100 but not as completely as we found it for BMI. To show this, we take the height predicted for a country in 2100 and subtract the height in that age group in the Netherlands in 2010 from this value. Averaging this over all age groups we find that by 2100 on average the male populations are only 2.2 cm smaller and the female populations are only 1.9 cm smaller than in the Netherlands. The largest remaining differences per sex are the Philippines' male age-groups which are on average still 10.8 cm smaller and the female age-groups of Timor-Leste which remain on average 8.6 cm smaller by 2100.

We can compare the height increase in this scenario with the historic change in the mean height of the 18 year olds in each country. Over the 90 year time horizon of this paper our scenario estimates an increase of up to 11.2 cm in height among men (in Bahrain, Kuwait, Palestine, and Saudi Arabia) and up to 11.4 cm in women (in the Comoros). The median increase among countries is 8.8 cm for men and 8.1 cm for women. While these values represent a significant increase in height, they lack behind historic values. For the 100 years between 1896 and 1996 NCD Risk Factor Collaboration (2016a) estimate that the largest increases have occurred in South Korean women (20.2 cm) and Iranian men (16.5 cm). They also find that in many European, North American, and highly developed Asian countries that experienced large increases in human height in the early 20th century, growth rates plateaued in the last decades of the 20th century. Assuming that this indicates a convergence towards an upper limit in human heights, lower global increases, as in our specification, seem reasonable.

[4] To be exact the Netherlands were reported to be the country with the tallest average height in a cohort of men at age 18, while the tallest women were found in Latvia (NCD Risk Factor Collaboration, 2016a).

4.4 Scenario 4: Increase in height and BMI

In the last scenario we estimate the change in calorie requirements if both, height and BMI increase in the future. This might be considered the most realistic scenario as this is what was observed in the past decades. Also, increments in the average BMI are likely to go along with better nutritional status of mothers and children, thereby being correlated with an increase in height of the newborn children.

We use the same assumptions as before in calculating the increase in both factors. Yet, the rise in calorie requirements is not simply the sum of the effects of both increases. This is due to the multiplicative relation between BMI and height.

5 Results

Our estimations, plotted in Figure 1, show an increase in global aggregate calorie requirements that slows down over time. In the baseline scenario, holding weight per age-sex group stable, we estimate an increase in calorie requirements by 61.07 percent between 2010 and 2100. In scenario two -increase of BMI to Mexican levels- we estimate an increase by 71.75 percent. In scenario three -increase of height to Dutch levels- the value is with 68.20 percent considerably smaller. Looking at Figure 1 shows that scenario two is always associated with larger increases than in scenario three, yet the difference starts to decline in the last third of the century. This reflects the much faster growth of BMI compared to height in our model. While many countries have already reached Mexican BMI levels by 2100, growth is still increasing in some countries. When combining both factors in scenario four the increase is estimated to be 79.80 percent. Compared to the baseline scenario this is a difference of 18.73 percentage points. As expected this value is larger than the sum of increases in scenario two and three, yet with only 0.92 percentage points this difference is comparably small.

Figure 1: Global calorie requirements up to the year 2100

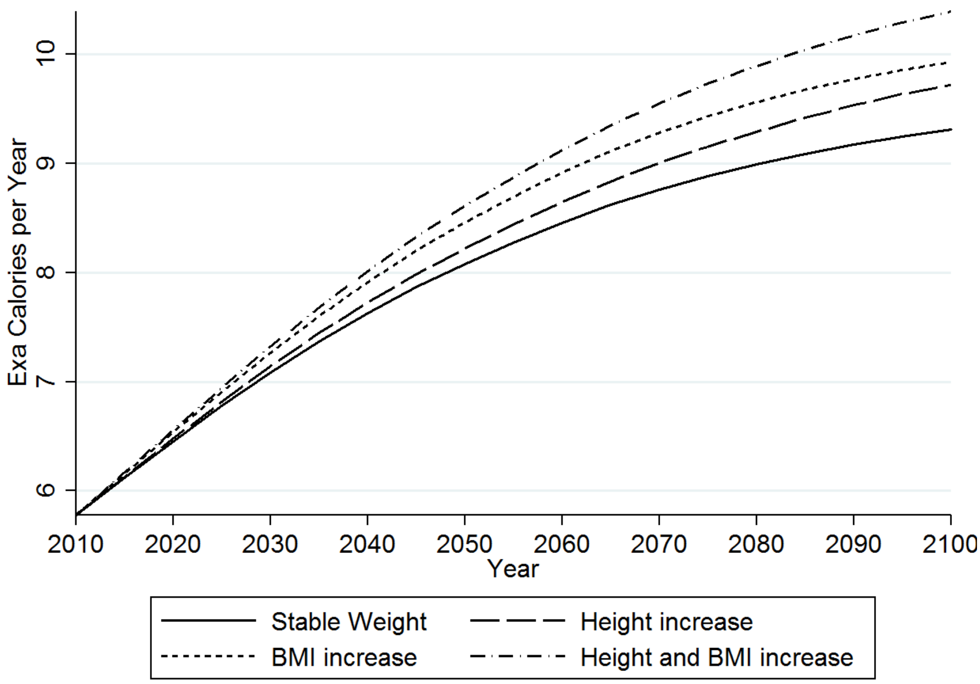
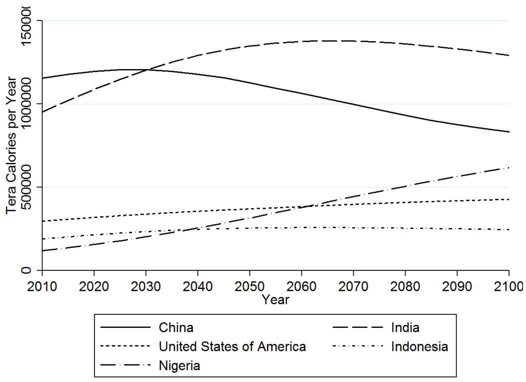


Figure 1 further shows that increases due to demographic change are triggering particularly high growth rates in energy requirements in the first half of the 21st century. While increases due to demography level-off after this point (as population growth is estimated to slow down), the effects due to increases in height and BMI still become larger. Hence, ignoring possible increases in BMI and height leads to an underestimation of the change in energy requirements particularly in the second half of the 21st century.

5.1 Changes at the country level

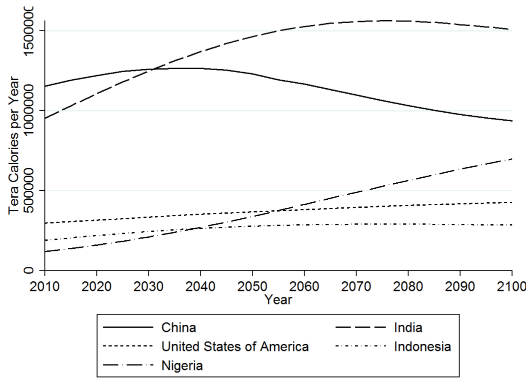
Disaggregating the numbers at the country level shows that not only the global requirement increases but also its geographical dispersion changes (see Table 7 for data on all 191 countries). We show the estimated development in the four largest countries by calorie requirements, as estimated in the baseline scenario (Figure 2) and in scenario four (Figure 3). As the fourth largest country changes from Indonesia in 2010 to Nigeria in 2100, both countries are included. First the comparison of estimates for China and India is noteworthy. In both scenarios, China will have an early peak in requirements and is then surpassed by India. This is mainly driven by demography: China will face a sharply declining population while India's population is projected to grow much longer. Similarly, calorie requirements in the United States will peak towards the end of the century due to steady population growth. And rapid population growth will propel requirements in Nigeria in both scenarios. But there are also important differences between the scenarios. It can be seen that besides the difference in levels between the two graphs, also the relative change amongst the countries intensifies. In particular the peak in Indian requirements is more pronounced and Nigeria takes over the third position much quicker and ending up further ahead of US aggregate requirements in scenario four.

Figure 2: Calorie requirements in the four largest countries in Scenario 1



Development of calorie requirements in the four largest countries in exa calories over time in the baseline scenario. As Nigeria joins the group and Indonesia is leaving it, predictions for both are plotted. *Source*: Own estimations.

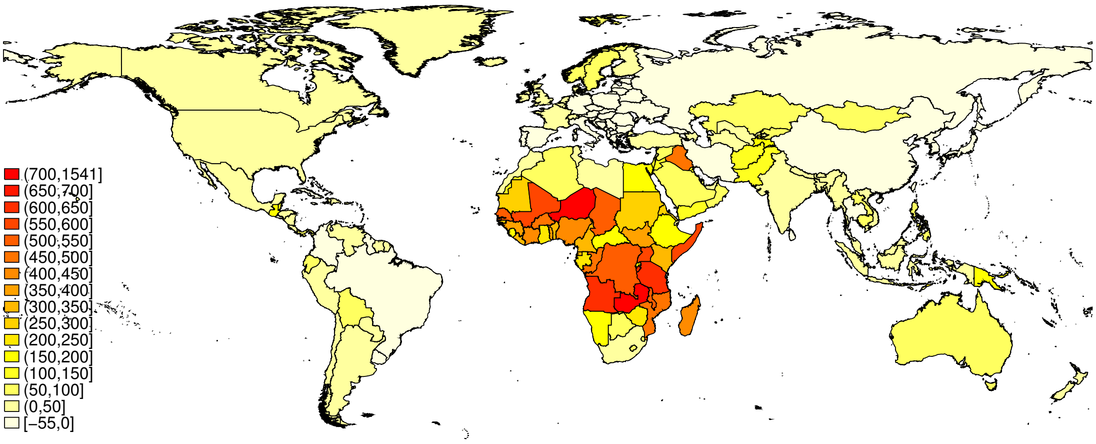
Figure 3: Calorie requirements in the four largest countries in Scenario 4



Development of calorie requirements in the four largest countries in exa calories over time in scenario four. As Nigeria joins the group and Indonesia is leaving it, predictions for both are plotted. *Source*: Own estimations.

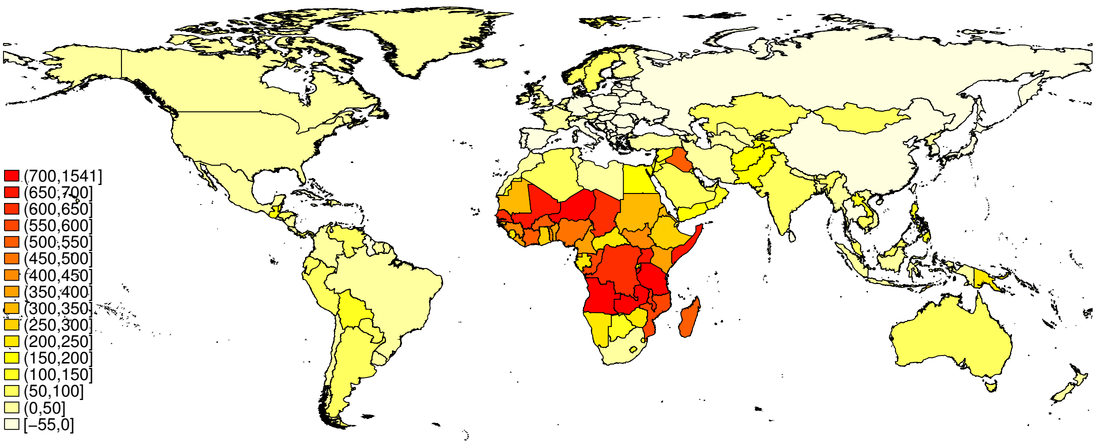
Nigeria is typical for Sub-Saharan Africa in its fast increase. Overall, it is African countries that experience the highest relative increases as is visible in Figures 4 and 5. Southern Africa is the exception to this trend, being more comparable to the more modest increases in most of the MENA region. In the latter countries with very low increases, like Morocco, Tunisia, Libya, and Turkey, exist beside Iraq, which experiences the strongest relative increase of any country outside of Africa. In between are a number of countries, including the strongly populated Egypt, which also experiences increases by 155 percent in the baseline scenario and 165 percent in the fourth scenario. Many European countries, especially in the former Socialist regions, experience a decline in energy requirements. The only European countries for which we estimate increases above 50 percent are Luxembourg, Norway and Sweden. The negative growth rates estimated for former Socialist countries also apply to Russia, China, and the Caucasus, except Azerbaijan. Together with declines in Iran, Japan, Sri Lanka, Taiwan, and Thailand, changes in these countries help to absorb parts of the expected increase in requirements in Asia. Still, strong relative increases in Pakistan, Afghanistan, Central Asia and parts of South East Asia can be observed at the same time. In absolute terms much more important is the moderate relative increase in India, which due to its population size dominates absolute changes in Asia. The Americas see only a relatively modest increase. A rise by more than 100 percent is only expected in Belize, Bolivia, and Guatemala.

Figure 4: Map of relative changes in Scenario 1



Relative change in national calorie requirements between 2010 and 2100 assuming stable weights (first scenario).

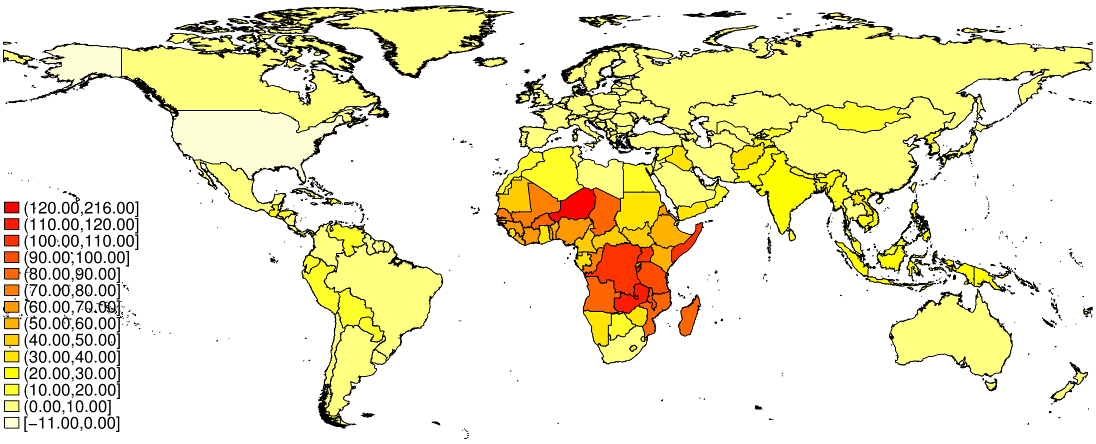
Figure 5: Map of relative changes in Scenario 4



Relative change in national calorie requirements between 2010 and 2100 assuming increases in BMI and height (fourth scenario).

Taking predictions made under scenario four we can look into the details of change. Among the 22 countries for which we estimate a more than five fold increase, Iraq (with an increase by 503 percent) is the only country that is not located in Sub-Sahara Africa. The three largest growth rates we estimate are Niger (1541 percent), Zambia (833 percent), and Burundi (725 percent). Likewise three of the five countries with the largest absolute increases are African, as can be seen in Table 2. The strongest

Figure 6: Map of relative changes due to increases in BMI and height



The Map shows the difference resulting from subtracting relative change between 2010 and 2100 in Scenario 1 from change in Scenario 4. It illustrates the estimated effect of increases in BMI and height on the increase in energy requirements.

decreases in absolute numbers are geographically more dispersed (Table 3). The relative decreases are clearly dominated by former socialist countries. They make up four of the top five countries in this group (Bosnia and Herzegovina, Bulgaria, Moldova, and Romania) with the exception being Taiwan. The estimated decline in these countries varies between 53 percent in Moldova and 43 percent in Taiwan.

Table 2: Countries with the largest absolute increase in calorie requirements in Scenario 4.

Country	Absolute increase in tera calories
Nigeria	577,620
India	555,977
DR Congo	311,276
Tanzania	238,924
Pakistan	201,488

Top five countries with the largest absolute increase in calorie requirements in scenario four (increase in height and BMI).

Table 3: Countries with the largest absolute decrease in calorie requirements in Scenario 4.

Country	Absolute decrease in tera calories
China	218,582
Japan	29,581
Russia	21,200
Thailand	17,331
Ukraine	17,273

Top five countries with the largest absolute decrease in calorie requirements in scenario four (increase in height and BMI).

5.2 Localizing the influence of weight gains

Including the influence of weight gains is not only important due to its effect on world energy requirements but also as it hits some regions more then others. In order to illustrate this, we map the difference between the predicted increase between 2010 and 2100 in scenarios four and one, i.e. the additional increase due to changes in BMI and height, in Figure 6.

It is clearly visible that the effect of changes in weight is stronger where we already expect the highest increases based on demographic changes. In part this is due to the gains in weight being multiplied with an increasing number of people, thereby amplifying the effects of demographic change. The other factor is that especially those countries where we expect stronger population growth are characterized by comparably low height and BMI in 2010. Countries with a population that is already tall and has a high BMI in 2010 cannot increase these values much more until they reach Dutch and Mexican levels respectively. For example, being home to a relatively tall population with a high BMI, the United States would require less calories as their BMI reduces to Mexican levels.

5.3 Comparing required with available calories

Our estimates are about required calories for a diet that maintains given or increasing weight of everyone in the world. This is a normative concept that might bear little relation with the actual availability of calories for human consumption which additionally is unequally distributed. Comparing our 2010 estimates to estimations of actually available calories thus helps to put our numbers into perspective and get an intuition of the future challenges to food security. Doing this we calculate the average calorie requirement per person and day and compare it to the calories available for consumption per person and day as calculated based on the food balance sheets for 2010 (FAO Agriculture and Economic Development Analysis Division, 2015).

In 2010 global food production exceeded the global energy requirements by on average 923 kcal per capita and day, yet in many countries there were insufficient calories available to meet everybody's requirements. We list these countries in Table 4. Next to the just described numbers we list the 3-years average food deficit in kcal per person and day according to the FAO (FAO Agriculture and Economic Development Analysis Division, 2015). For Antigua and Barbuda as well as Granada no numbers where available for this last point. In all countries where numbers are available the food deficit calculated by the FAO is larger than our calculations. This is not only because it is the average over three years but also due to a number of conceptual differences. While FAO Agriculture and Economic Development Analysis Division (2015) is likely to arrive at lower energy requirements per person, using an estimate for the lowest healthy BMI and a PAL of 1.55, it also takes into account the unequal distribution of food in each country. This later point is likely to be the reason for the higher calorie deficits and the overall larger number of 114 countries with a deficit in the three year average in 2010. Considering the impact of unequal distribution of calories, the required nutritional energy is considerably higher than our estimations suggest. More importantly, inequality will also have an effect on the necessary increase in the available calories to meet future requirements. How strong this influence will be, depends on a number of factors (e.g. income levels and distribution, food prices, infrastructure) that are beyond the scope of this paper.

Similarly, substantially more calories will need to be produced if the current trend of rising meat consumption continues (as grain calories are fed to animals and generate a much lower number of calories from in form of animal products), food waste increases, or more calories are used to produce non-food products such as biofuels.

Table 4: Comparison of required and available calories in 2010

Country	Available kcal (avg. p.c. & day)	Required kcal (avg p.c. & day)	Surplus kcal (avg p.c. & day)	FAO food deficit kcal (3-year avg p.c. & day)
Antigua and Barbuda	2316	2443	-127	-
Bolivia	2177	2218	-41	182
Botswana	2234	2282	-48	227
Grenada	2432	2440	-8	-
Haiti	2169	2233	-64	503
Namibia	2055	2201	-146	278
North Korea	2089	2247	-158	341
Tajikistan	2105	2267	-162	292
Zambia	1904	2030	-126	442

Comparison of estimated average per capita and day calorie requirements with calories available for human consumption in 2010, the difference between the two (i.e. the surplus kcal), and the three years average food deficit in kcal per capita and day. For Antigua and Barbuda and Grenada no information on the last point is available.

6 Conclusion

Our estimates show that changes in body weight considerably contribute to the expected increase in future national and global calorie requirements. This would be particularly important in the second half of the 21st century, when increases due to demographic change start leveling off. The additional increases will especially affect those regions where already demographic change leads to markedly higher energy requirements. To the fact that high BMI levels are generally considered to be a problem of increasing importance due to their negative effects on health (e.g. Forouzanfar *et al.* (2016)), we therefore add an additional reason to stop global trends towards overweight and obesity.

While we focus on energy requirements in this paper, the larger interest relates to the future needs for food production and distribution necessary to ensure food security. Energy requirements are only one factor affecting food demand. Three other distinctive factors will have a major role: First, a considerable share of food items is lost or wasted. Agricultural production would therefore need to produce additional calories to make up for the losses. The extent of this will depend heavily on production systems, organization of the supply chain, and consumption patterns. The effect of these factors is currently visible in the variation in food loss which can be observed over regions and food groups (Gustavsson *et al.*, 2011). Second, the consumption of meat and dairy products acts as a multiplier on the demand for agricultural goods as producing these goods needs additional energy in the form of feeds. Predictions on future demand foresee slower growth rates around 1.3 percent per annum between 2005/2007 and 2050, not least because many countries already reached fairly high meat consumption levels (Alexandratos and Bruinsma, 2012). It is unclear how exactly increased calorie consumption due to rising weights would affect the demand for meat and dairy products. One indication is that protein requirements rise with the amount of lean tissue in a body (WHO/FAO/UNU, 2007). If meat and dairy products are used to cover this requirement, weight increases will raise the demand for meat and dairy products. Yet, dietary patterns are not necessarily time persistent and price effects will play an important role in the determination of demanded quantities vis a vis other protein sources. Third, inequalities in the distribution will increase the amount of food needed to ensure zero hunger. The importance of this factor was discussed in section 5.3.

When comparing our results to other estimations on future developments in food security (e.g. Alexandratos and Bruinsma (2012)), it is important to distinguish exactly which goal should be reached. Our calculations relate to the calories that a person needs to sustain a given body weight. Setting this as a goal requires a particular normative decision. If the goal is to ensure the capability of every person to make free decisions on their nutrition, our estimations might be a useful approximation. Still, even when not making this normative decision, our results show that rising human weights will have a sizable effect on what people most likely would like to eat given that they want to keep that weight. In economic terms this relates to a higher preference for food. The latter would translate to an upward shift in the demand for food and ultimately an increase in food prices at any given supply curve. Importantly this upward shift would primarily be observable in countries that already face higher calorie demand due to population growth. Therefore, it puts an even heavier burden on countries that will already have trouble meeting requirements irrespective of this factor. Combined with the modest effect of weight increases on countries with smaller population growth, the problem could at least partially be solved via trade. Yet this would require countries with rapidly increasing requirements to have sufficient purchasing power. Given that the increase in food requirements is especially high in regions that are currently suffering from low levels of economic development, ensuring a sufficient supply of calories is likely to depend on some form of redistribution, or substantial improvements in economic development there. Of course, one may also argue that in those countries that are unable to secure enough calories to feed their growing populations, not gaining weight or increasing height will be one of the responses to partly address this problem. To the extent that people are overweight, one might even argue that this could be beneficial from a health perspective (given that all other nutritional requirements are still met). But such adjustments to insufficient caloric availability are rarely smooth and equitable. A more likely scenario would be that this would be accompanied by starvation for many, often affecting the most vulnerable groups the most.

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Appendices

A Appendix of tables

Table 5: Replacements for countries with missing data on height

Country	replaced with data from
Andorra	Spain
Bahrain	Saudi Arabia
Bhutan	India
Equatorial Guinea	Sao Thome & Principe
Micronesia, Federated States of	Vanuatu
Puerto Rico	USA
Qatar	UAE
Singapore	South Korea
Tonga	Vanuatu

Countries with missing data on height and the countries that were used to replace the missing data.

Table 6: Replacements for countries with completely missing data

Country	replaced with data from	Merged into
Aruba	Saint Kitts and Nevis	
Curacao	Netherlands	
French Guyana		France
Guadeloupe		France
Guam		USA
Macao		PRC
Martinique		France
Mayotte		France
New Caledonia		France
Reunion		France
South Sudan	Sudan	
US Virgin Islands		USA
West Sahara	Morocco	

Countries and territories with missing data on height and/or BMI and the countries' data that where used to replace the information or into which the population was merged.

Table 7: Relative changes in calorie requirements between 2010 and 2100 by country

Country	Stable Weight pct.change	Rising BMI pct. change	Rising Height pct. change	Rising Height & BMI pct. change
Afghanistan	127	135	149	158
Albania	-41	-38	-40	-37
Algeria	70	76	79	85
Angola	627	660	681	717
Antigua and Barbuda	31	38	31	38
Argentina	44	51	45	51
Armenia	-40	-38	-39	-36
Aruba	-18	-13	-19	-15
Australia	89	93	90	94
Austria	-3	-1	0	2
Azerbaijan	5	10	6	12
Bahamas	37	44	36	44
Bahrain	20	27	25	33
Bangladesh	11	16	24	30
Barbados	-9	-6	-8	-5
Belarus	-29	-27	-27	-26
Belgium	19	22	21	24
Belize	120	128	119	128
Benin	305	325	337	359
Bhutan	9	14	17	23
Bolivia	89	100	96	107
Bosnia and Herzegovina	-52	-51	-50	-50
Botswana	86	93	97	105
Brazil	0	5	3	8
Brunei	22	31	25	35
Bulgaria	-55	-54	-54	-53
Burkina Faso	463	488	517	546
Burundi	609	642	687	725
Cabo Verde	40	45	49	54
Cambodia	67	77	86	97
Cameroon	332	351	359	380
Canada	43	47	43	47
Central African Republic	200	215	228	246
Chad	542	567	603	632
Chile	14	21	14	21
China	-28	-24	-23	-19
China (Hong Kong SAR)	8	13	14	21
Colombia	-1	3	1	6
Comoros	250	269	274	295
Congo	477	505	523	555
Costa Rica	8	15	10	17
Cote d'Ivoire	437	464	473	503
Croatia	-40	-39	-39	-38
Cuba	-39	-37	-37	-34
Curacao	41	41	44	44
Cyprus	23	29	22	28
Czech Republic	-18	-16	-18	-17
DR Congo	546	575	614	649
Denmark	22	23	26	27
Djibouti	39	47	50	59
Dominican Republic	23	30	27	34
Ecuador	67	76	70	79
Egypt	155	168	151	165
El Salvador	-26	-22	-24	-21
Equatorial Guinea	335	357	357	382
Eritrea	256	271	300	319
Estonia	-33	-32	-32	-31
Ethiopia	195	209	235	252
Fiji	-18	-15	-17	-14
Finland	8	10	9	11
France	22	25	25	28
French Polynesia	8	11	6	9
Gabon	206	220	221	236
Gambia	477	507	518	552
Georgia	-43	-41	-43	-41
Germany	-23	-22	-22	-21
Ghana	218	234	239	257
Greece	-35	-33	-36	-33

Grenada	-31	-29	-29	-27
Guatemala	151	162	159	171
Guinea	379	402	420	446
Guinea Bissau	259	276	288	308
Guyana	-19	-15	-16	-13
Haiti	40	46	50	57
Honduras	46	52	51	59
Hungary	-36	-34	-35	-33
Iceland	20	21	23	23
India	36	42	51	58
Indonesia	29	37	41	50
Iran	-8	-3	-5	0
Iraq	472	501	474	503
Ireland	38	41	37	41
Israel	141	147	142	148
Italy	-18	-15	-17	-14
Jamaica	-38	-35	-36	-34
Japan	-36	-33	-31	-28
Jordan	132	143	127	139
Kazakhstan	54	62	56	64
Kenya	320	335	356	372
Kiribati	151	158	146	153
Kuwait	110	118	105	113
Kyrgyzstan	71	80	75	84
Laos	68	84	84	103
Latvia	-40	-39	-39	-38
Lebanon	8	12	7	12
Lesotho	85	94	96	106
Liberia	335	361	364	393
Libya	33	38	33	38
Lithuania	-36	-35	-36	-35
Luxembourg	100	104	101	105
Macedonia (TFYR)	-30	-28	-28	-26
Madagascar	434	459	491	520
Malawi	538	574	591	633
Malaysia	44	53	51	60
Maldives	32	40	39	47
Mali	582	596	640	655
Malta	-17	-12	-18	-13
Mauritania	288	308	309	331
Mauritius	-25	-21	-22	-18
Mexico	26	36	26	36
Micronesia (Fed. States)	19	22	17	20
Moldova	-56	-54	-55	-53
Mongolia	65	74	71	81
Montenegro	-31	-29	-29	-27
Morocco	28	34	33	40
Mozambique	470	500	522	557
Myanmar	10	15	20	26
Namibia	176	188	195	209
Nepal	13	19	24	32
Netherlands	2	2	5	5
New Zealand	39	42	38	41
Nicaragua	24	30	27	34
Niger	1326	1391	1464	1541
Nigeria	412	438	449	478
North Korea	0	4	9	15
Norway	59	61	62	63
Palestine	320	337	316	333
Oman	89	99	95	106
Pakistan	125	133	141	150
Panama	68	75	72	79
Papua New Guinea	177	190	190	204
Paraguay	43	50	48	55
Peru	43	51	47	55
Philippines	86	92	101	108
Poland	-44	-42	-43	-41
Portugal	-31	-28	-30	-27
Puerto Rico	-42	-38	-42	-39
Qatar	62	70	59	67
Romania	-48	-46	-47	-45
Russian Federation	-19	-17	-18	-16
Rwanda	165	177	195	210

Saint Lucia	-4	0	-6	-2
Saint Vincent (a. t. G.)	-29	-26	-28	-24
Samoa	53	60	44	50
Sao Tome and Principe	239	256	257	276
Saudi Arabia	72	81	71	80
Senegal	525	545	577	600
Serbia	-42	-41	-41	-40
Seychelles	-14	-12	-12	-10
Sierra Leone	171	185	195	211
Singapore	6	10	13	17
Slovakia	-32	-31	-32	-31
Slovenia	-20	-19	-19	-17
Solomon Islands	176	187	188	200
Somalia	561	598	623	667
South Africa	31	38	33	40
South Korea	-26	-23	-20	-17
South Sudan	353	376	374	400
Spain	-20	-16	-19	-16
Sri Lanka	-27	-24	-21	-17
Sudan	281	301	299	321
Suriname	8	12	9	14
Swaziland	86	95	91	101
Sweden	53	54	56	57
Switzerland	41	44	45	48
Syria	93	104	93	103
Taiwan	-49	-46	-46	-43
Tajikistan	156	167	167	179
Tanzania	610	645	665	704
Thailand	-40	-36	-36	-31
Timor-Leste	222	238	262	282
Togo	368	391	404	431
Tonga	66	64	57	55
Trinidad and Tobago	-26	-24	-26	-24
Tunisia	17	21	21	25
Turkey	23	29	23	29
Turkmenistan	14	19	17	22
Uganda	571	604	635	674
Ukraine	-43	-42	-42	-41
United Arab Emirates	44	51	44	51
United Kingdom	30	33	31	34
USA	44	46	41	44
Uruguay	-2	1	-2	2
Uzbekistan	19	24	22	28
Vanuatu	205	213	215	223
Venezuela	46	55	48	57
Vietnam	16	21	30	36
West Sahara	103	113	112	122
Yemen	132	145	149	163
Zambia	715	755	786	833
Zimbabwe	209	223	232	248

Relative increase in calorie requirements between 2010 and 2100. The columns show the results from each of the four scenarios.