



Global food waste across the income spectrum: Implications for food prices, production and resource use

Emiliano Lopez Barrera*, Thomas Hertel

Agricultural Economics Department, Purdue University, United States

ARTICLE INFO

Keywords:

Food waste
Food security
Sustainability
Global food economy

JEL codes:

Q11
Q18

ABSTRACT

There are few examples in the existing literature that address the quantitative linkages between food waste, food security, and environmental sustainability, at global scale. Here we develop a new panel database on household food waste at the national level based on the Energy Balance equation, including adjustments for changes in body weight over time. We use this to characterize the non-linear relationship between per capita income and the share of food availability wasted. By incorporating this relationship into a global partial equilibrium model of the agricultural sector (SIMPLE), we develop future trajectories of household food waste. We find that the emerging economies, particularly China and South Asia, are likely to play a key role in determining global food waste at mid-century. We also present several counterfactual scenarios that shed light on the implications for environmental and food security of limiting future growth in food waste. We find that the global impacts of these alternative pathways are greatly enhanced in the context of a more open international trade regime.

1. Introduction

Sustainably meeting the food demands of a growing population based on finite resources while protecting the environment is one of the great challenges of humanity in the coming decades. Current trends in population and consumption preferences will continue boosting demand for food for at least another 40 years (Godfray et al., 2010). In this context, increasing food supplies as well as decreasing food losses and waste are key to meeting these demands. While the existing literature has mainly focused on increasing production, the magnitude of loss and waste is too large to be ignored (Irfanoglu et al., 2014; FAO, 2019b). Roughly, one-third of the edible parts of global food produced for human consumption is estimated to be lost or wasted (FAO, 2015), and these losses have been valued at 1 trillion USD (FAO, 2013). Resources used in the production of food that ends up being lost and wasted accounts for almost one-fourth of the overall global cropland and fertilizer use (Kummu et al., 2012) contributing around 3.3 Giga-tonnes of CO₂-equivalent methane emissions (FAO, 2013).

Food lost and wasted also presents a social dilemma, given the persistence of global hunger. Food waste at the consumer level in industrialized countries (222 million tons) is almost as high as the total net food production in Sub Saharan Africa (SSA) (230 million tons) (FAO, 2015). Yet even as food loss and waste is rising, the global population facing chronic food deprivation has also been increasing,

growing from 804 million in 2016 to around 821 million in 2017 (FAO, 2019c). Food waste is concentrated in the industrialized countries, where more than 40% of the food losses and waste occur at retail and consumer (households and retailers) levels (FAO, 2015) and private households are responsible for the largest share (Monier et al., 2010). Responding to these apparent contradictions, food loss and waste has received growing attention from policymakers, as well as from academics, at local, regional, and global levels. Indeed, it is included as part of the United Nation's 2030 Agenda for Sustainable Development.

One barrier to reducing food loss and waste is the lack of data at the national and international level. Responding to this deficiency, FAO has developed the Food Loss Index to estimate how much food is lost in production or in the supply chain before it reaches the retail level. According to FAO 2019, 14% of food is lost through the supply chain before reaching the retail level. However, little is known about how much food is wasted by consumers (households and/or retailers). As a result this lack of data, there are few credible studies of the linkages between consumers' food waste, food security, and environmental health (Hall et al., 2009; Verma et al., 2017, 2020). Despite the attempt to develop a systematic framework for food loss and waste based on the life cycle of a typical food item by Bellemare et al. (2017), in general, the inconsistency of measures of food loss and waste has contributed to the absence of a coherent policy framework towards sustainable food consumption (Reisch et al., 2013; Bellemare et al., 2017).

* Corresponding author.

E-mail addresses: wlopezba@purdue.edu (E. Lopez Barrera), hertel@purdue.edu (T. Hertel).

<https://doi.org/10.1016/j.foodpol.2020.101874>

Received 28 August 2019; Received in revised form 17 February 2020; Accepted 24 February 2020

0306-9192/ © 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

The present study follows the definition proposed by the High-Level Panel of Experts on Food Security and Nutrition (HLPE 2014): “food loss and waste (FLW) refers to a decrease, at all stages of the food chain from harvest to consumption in mass, of food that was originally intended for human consumption, regardless of the cause”. The proposed definition HLPE (2014) distinguishes between food losses (FL) “occurring before the consumption level regardless of the cause” and food waste (FW), “occurring at the consumption level regardless of the cause” (emphasis added). This distinction between loss and waste is essential for the current study since we focus solely on food waste at consumers (households and retailers) level.

In this paper, we contribute to the literature by providing a novel framework to better understand the linkages between consumer’s food waste at the national level on the one hand, and global food security and environmental health on the other hand. We begin with a newly constructed panel data set on per capita daily uneaten calories using a basic energy balance equation. Given the lack of data on food waste the present paper also contributes by providing a global, internationally comparable data set on food waste. This allows for an empirical examination of the underlying systematic relationships between per capita income and the share of food waste in total food availability (SFW: the ratio of uneaten calories, divided by purchased calories).¹ This statistical relationship allows us to incorporate food waste into a global partial equilibrium model of the agricultural sector. With this framework in hand, we undertake projections of future food waste as well as analysis of the food security and environmental impacts of alternative scenarios in which future food waste is limited.

The paper is organized as follows. We start with a review of the current literature on food waste – focusing specifically on the regional and global scale implications. We then introduce the new international data set on food waste which forms the basis for a novel methodology for estimating the underlying relationship between per capita income and food waste. This allows us to incorporate food waste into our global partial equilibrium model of the agricultural sector. In the Section 5 we start by performing an historical validation of the model for the period 2006–2013. We then turn to a business as usual projection of global food waste to 2050. Finally, we evaluate the impact on food security and the environment of mitigating in food waste, emphasizing the key role for international market integration. The paper concludes with a discussion of our findings and the limitations on the present study, pointing to potential avenues for future research.

2. Literature review and knowledge gap

The Food and Agriculture Organization of the United Nations (FAO) reports the Food Balance Sheets (FBS), which is the most extensive global database on countries’ food systems. The FBS report annual data about domestic food supply (e.g., production, imports, and stock changes), and domestic food utilization (e.g., feed, seed, processing, export, etc.). FAO’s methodology is not free of criticism (Hall et al., 2009; Svedberg, 1999). It is believed to underestimate food availability in developing countries, particularly in rural areas where unreported subsistence production represents an important share of the households’ consumption bundle (Hawkesworth et al., 2010). Additionally, before the last revision of the methodology (FAO, 2019a) one of the components of the FBS (often stocks) would take on the outstanding unbalanced amount thereby inheriting all the statistical errors. The revised methodology reported by FAO mitigates some of those inaccuracies (FAO, 2019a) by improving the estimates of the specific modules through the supply chain (e.g., stocks, food, feed, loss, etc.). In the revised methodology, imputations for the FBS components not reported by countries are generated by dedicated modules and then a

balancing mechanism proportionally spread the imbalances out among all the components (FAO, 2019a). The new food loss module reports essential information of losses across the whole food value chain up to and excluding the retail level. However, the information related to food waste at the consumer level is still being revised (FAO, 2019a). Despite its limitations, FAO’s is the most widely used global database for food availability at country level. Based on the FBS Kummur et al. (2012) examine the relationship between crop-based food loss and waste throughout the entire supply chain and environmental sustainability. The authors estimate the potential resource savings and the impact on food supply from a hypothetical reduction on food waste. They find that around one quarter of the produced food (614 kcal/cap/day) is lost within the food supply chain, accounting for close to one quarter of the total resources used (fresh water, cropland and fertilizer).

There are several examples in the existing literature of country-based studies attempting to quantify the magnitude of food waste at the consumer (households and retail) level. Most of them focus on developed regions. Monier et al. (2010) provides a comprehensive meta-analysis data base for food waste in the European Union (EU) based mostly on data from the EUROSTAT database as well as through literature review. They find that total food waste in the EU27 (the EU except for the United Kingdom –UK–) in 2006 added up to 181 kg per capita per year (corresponding to 12 percent of the total EU food production). From which the 42 percent is generated by households (adding up to 23.3 million of tons). They also provide evidence of significant variability in per capita waste among the EU countries, with the highest food waste per capita generated in the Netherlands, Belgium and Cyprus. Thyberg et al. (2015) offer a meta-analysis and synthesis of state, county, and regional studies from 1989 and 2013 within the United States (US) based on the weight of food disposed in Municipal Solid Waste (MSW) in the US. They find that the aggregate food waste disposal rate per person per day was 0.615 lb (leading to an estimate of 35.5 million tons of food waste disposed annually in the US). The proportion of food waste in the overall MSW increased significantly during the 25 years analyzed in this study. The authors also find evidence of significant variations in per capita food waste across different regions.

Using a different framework, moving from quantifying weight to quantifying calories, Hall et al. (2009) developed a detailed mathematical model relating changes in body weight and food intake. This model allows the authors to calculate the energy content of food waste in the US, from the difference between the US food supply for consumption in kilocalories per capita per day (kcal/cap/day) and their estimations of food intake (kcal/cap/day). Their results show that per capita daily caloric waste in the US has increased by 50% since 1974, reaching around 1400 kcal/cap/day (around 40% of the available calories) by the year 2013.

There are few examples in the existing literature addressing the linkages between the reductions in food waste at the household level, on the one hand, and global food security and environmental sustainability, on the other. A key reason for this literature gap is the absence of reliable data on food waste at the national level (Hall et al., 2009; Xue et al., 2017; FAO, 2019b). The range of methods applied to quantify food waste also differs greatly from country to country (Xue et al., 2017; FAO, 2019b) making comparisons or integrated analyses nearly impossible. Indeed, there is not one unique definition of food waste. The absence of such a standard has contributed to a dearth of comparable data (Parfitt et al., 2010; Bellemare et al., 2017) leading to poorly informed efforts attempting to reduce food waste (Bellemare et al., 2017).

We can classify methods for quantifying food waste into two groups, those based on energy metrics (e.g. kcal) (Kummur et al., 2012; Hall et al., 2009; Hiç et al., 2016) and those based on weight metrics (e.g. kg, ton) (Monier et al., 2010; Thyberg et al., 2015). The former has the advantages of accounting for variation on nutritional content within each food type, providing information regarding the nutritional value

¹ Since the share of food waste is defined as a ratio it becomes a dimensionless variable.

of the food wasted (Lipinski et al., 2013) while also presenting a better opportunity for comparability across countries. Hiç et al. (2016) extend the methodology proposed in Hall et al. (2009) to calculate surplus in energy availability for 73 countries, linking the latter with Greenhouse Gas (GHG) emissions. Their results show how, given small changes in global energy requirement relative to large changes in food availability the food surplus has increased particularly rapidly in emerging economies (India and China). They also forecast a global food surplus of 850 kcal/cap/day by 2050, leading to an increase in associated GHG emissions in the range of 1.9–2.5 Gt Co2 equivalent/year. Springmann et al. (2018) analyze the environmental effects of the food system as well as options for mitigating those effects, including food waste and loss reductions, towards 2050. However, they base their analysis on current estimates of food waste, not on future projections. They find that, in the absence of yield improvements, technical change and moderating measures, the food system's broad effects on the environment could increase by 50–90%. The authors conclude that such a scenario would cause humanity to violate the planetary safe operating space. They also conclude that a synergistic combination of sustainability measures, including cutting food waste by 75%, will be needed to avoid serious environmental damages.

There are also some studies which have sought to evaluate the economic implications of food waste and its mitigation using applied general and partial equilibrium frameworks. Irfanoglu et al. (2014) explore the impacts of reducing food losses and waste on global food security, trade, greenhouse gas emissions, and land use by using the Simplified International Model of Crop Prices, Land Use and the Environment (SIMPLE) model (Baldos and Hertel, 2013). In this study the food waste is incorporated by including a household production function in the model, and the food waste is computed as the difference between food purchased and food consumed. However, they do not offer a methodology for projecting the future evolution of food waste. Britz et al. (2014) analyze the potential effects of food waste reduction on the whole economy incorporating food waste reduction related costs in a regional computable general equilibrium (CGE) model. They point out that, under certain circumstances, the attempts to reduce food waste might cause severe loss of competitiveness for the agriculture and food production sectors. Hertel and Baldos (2016b) examine the implications of a range of policy initiatives aimed at improving food security and environmental outcomes, including reductions in post-harvest losses in SSA and reductions in food waste in the wealthy economies. Their study uses the SIMPLE model as a framework, first in the context of historically segmented markets for the global food economy, and secondly in a hypothetical future world of fully integrated crop commodity markets. Their study is the first to point out the potential interaction of the policies to reduce food waste and loss with trade policies.

Verma et al. (2020) present a cross section data set with country-specific metrics of per capita daily caloric waste for 70 countries by extending the energy-balance equation presented in Hall et al. (2009). Their study starts by exploring the relationship between food waste, income, and prices concluding in an estimation of the affluence elasticity of waste (a metric for the influence of per capita income on food wasted). A limitation in this study is the absence of a time series component which stems from the fact that they do not consider changes in body weight in the energy balance equations. This limits the applicability of their study in examining the long-term underlying systematic relationships between income, food availability, and food waste. All of these model-based studies: Verma et al. (2020), Britz et al. (2014), Hiç et al. (2016), Irfanoglu, et al. (2014), Hertel and Baldos (2016b) and Springmann et al. (2018) fail to provide a systematic analysis of the long-term relationship between national per capita income growth and food waste.

The present research differs from the aforementioned studies in a number of important ways. We start by extending the methodology used in Hall et al. (2009), Hiç et al. (2016), and Verma et al. (2020), to

calculate daily caloric per capita waste by incorporating changes in body weight into the analysis and extending coverage to a time series encompassing 95% of the world's population. This results in a new panel data set of country-specific average daily per capita calories wasted from 1975 to 2014 for 158 countries. While previous studies have focused on the implications of reducing current levels of food waste (Springmann et al., 2018), we use these data to estimate a model of food waste evolution across the development spectrum which allows for more accurate projections of consumer food waste. These estimates are then incorporated into a global model to shed light on how food waste affects food security and environmental health towards 2050. Finally, we analyze several counterfactual scenarios on how limiting future evolution of food waste would affect food security and the pressure on environmental resources, paying special attention to how these impacts are influenced by the extent of international market integration.

3. Food waste measurement methodology and the long-term relationship with income

3.1. A new panel data set for global food waste

We begin by creating a consistent, international panel database building on the energy balance equation. Since food waste at the country level is not directly observed at present, we must infer this from other observables, including food availability (FA), estimates of physical activity levels (PAL) and basal metabolic rates (BMR), and changes in Body Mass Index (BMI). This leads to the following system of equations for deducing food waste:

$$\text{Energy Expenditure} = \text{Physical Activity Level} \times \text{Basal Metabolic Rate} \quad (1)$$

$$\text{Food Intake} = \Delta \text{Body Weight} \times \rho + \text{Energy Expenditure} \quad (2)$$

$$\text{Food Waste} = \text{Food Available} - \text{Food Intake} \quad (3)$$

where ρ is a parameter which converts changes (increases) in body weight to excessive intake of calories based on the energy balance equations (Hall et al., 2011). Following this approach, the uneaten calories at household level are quantified as the difference between the available calories (kcal/cap/day) and the caloric intake (kcal/cap/day). Country-specific food availability (kcal/cap/day) is obtained from the FAO Food Balance Sheets (FAO/WHO, 2017) over the period 1975–2013. The country-specific average Energy Expenditure are calculated from the product of country-specific BMR and the country-specific PAL. The composite BMR, for an average person in each country, is a function of countries' demographics (age, average weight, and sex) retrieved from World Bank Database (World Bank, 2018). PAL based on different lifestyles retrieved from (FAO/WHO, 2004). We extend Verma et al. (2020) by incorporating the increment of body weight into this equation. The country-specific average increase $\Delta \text{Body weight}$ (BW) was obtained from the differences in BMI reported for the years 1975, 1985, 1995, 2005, and 2014 (Abarca-Gómez et al., 2017) and country-specific average height for male and female from NCD Risk Factor Collaboration (Risk and Collaboration, 2016). The increment in body weight is converted to energy (Kcal/cap/day) by applying a weight change model (Hall et al., 2011). Finally, by assuming a uniform intertemporal distribution of changes on energy expenditure due to changes on average weight, we can calculate country-specific average annual energy daily intake for the period 1975–2013. This extension is critical to permit estimation of the underlying long-term relationships between income, prices, food availability, and food waste.

Previous evidence suggests that per capita income plays a key role in the evolution of food waste, both due to an increase in food purchases per capita and an increase in the opportunity cost of household labor (Xue et al., 2017). Previous studies suggest this relationship to be nonlinear, wherein the responsiveness of food waste to changes in income is high for developing countries and falls as nations become

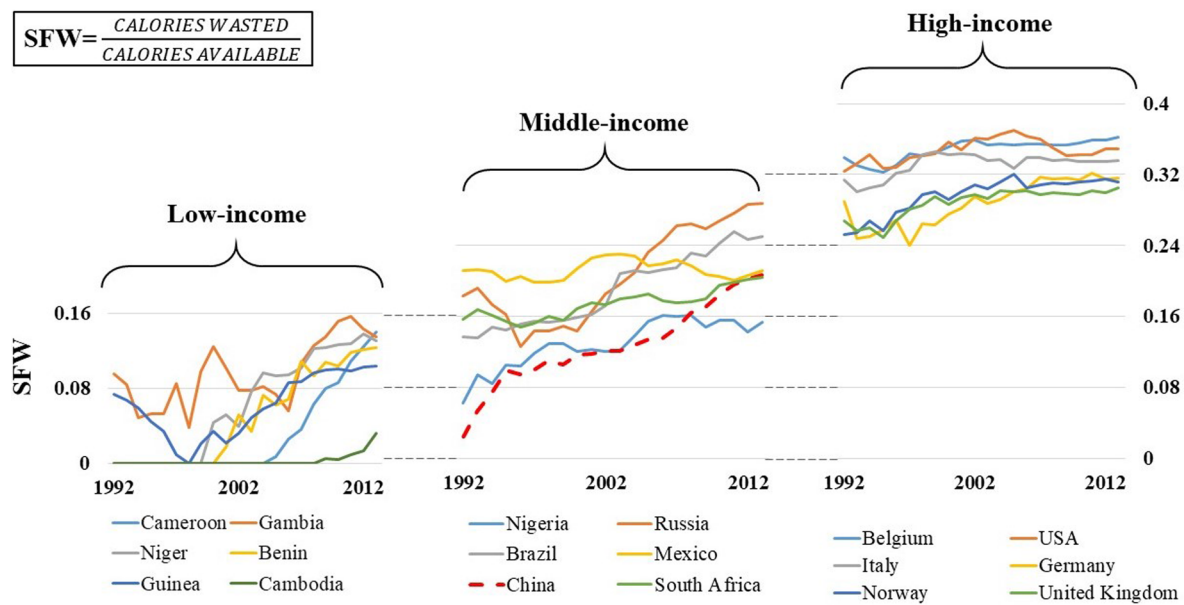


Fig. 1. The Share of Food Waste (SFW) across the income spectrum using a subset of 18 countries (selected from the 158 used in the present study) grouped by income levels according to World Bank Classification 2018.

richer. Here, we use our newly constructed data set to explore this relationship in greater depth.

We find it useful to focus on the share of food waste in a country's total food supply, as opposed to the absolute level of waste (Verma et al., 2020; Carmona-Garcia et al., 2017; Xue et al., 2017; Zhou and Yu, 2014). We define the Share of Food Waste (SFW) as the ratio of daily per capita calories wasted over the per capita calorie availability. Then we compare the evolution of the SFW across income regions, as well as across countries over time. Fig. 1 presents an illustration of the findings based on a subset of 18 countries in our data set, chosen to represent a variety of geographic regions as well as different levels of development.

A first point to be observed in Fig. 1 is that, on average, the per capita daily energy supply has exceeded the requirements for most of the countries in our sample since 1992. That is also true at the global level, where the gap between the calories available and required, for an average person, have firmly increased in the recent decades (see Fig. A1 in Appendix A). The global SFW has increased from 0.11 to 0.17 over the 1992–2013 period. Of course, it should be noted that this does not mean that every person is obtaining sufficient calories, due to the wide distribution of caloric intake within each country. Understanding the intra-country distribution of food (food accessibility), is beyond the scope of this study given the level of aggregation in our approach. A second observation is that, in low-income countries, SFW rises rapidly as per capita incomes increase. Middle-income countries illustrate a transition period during which the absolute amount of food waste rises rapidly, while the rate of growth slows. Finally, high-income countries appear to converge to a relatively stable level of SFW. In this sample of 18 countries, SFW ends up stabilizing in the range between 29% and 36%. The UK is at the low end of this range – perhaps indicative of the strong emphasis placed on reducing food waste in the UK starting in 2007 (Defra, 2007). On the other hand, the US is near the top of this group, peaking around 37% in 2004, consistent with figure reported in Hall et al. (2009), before dropping to 34.6% by the year 2013. Of course, a steady share of food waste in total availability is not equivalent to constant per capita food waste, since availability, as well as body mass have continued to rise in most regions.

The consistency of our results with those of Hall et al. (2009) is important, as it provides an indirect channel for validating our approach, which is inspired by those authors. In their paper, focusing only on the US, Hall et al. (2009) compare their estimates of total food waste

to data on US municipal solid food waste and find a close correspondence. Their estimates move closely over time with the observed data on municipal food waste, although their predictions of food waste are consistently above the solid food waste time series. This makes sense for several reasons. Firstly, not all waste goes to municipal dumps. And secondly, the solid food waste observations are likely underestimates of the true values of municipal waste. An additional source of indirect validation of our approach comes from the fact that it suggests a leveling off of food waste at higher income levels that is consistent with the findings in the extensive literature review on food waste measurement and data provided by Xue et al. (2017) along with evidence that the income elasticity of calories purchased and wasted decreases with rising incomes (Zhou and Yu, 2014; Verma et al., 2020).

Fig. 2 aggregates the food waste data from all 158 countries in our data set to the global level, showing the contribution of major country groupings to global, per capita food waste over the period 1992 to 2013. The size of the “pies” correspond to how the estimated “global” per capita food waste has increased in this sample of countries since 1992 – starting at 287 kcal/capita/day and rising to 473 by 2013, with a projected 72% increase reaching 812 kcal/capita/day by the 2050 (see Section 4 below). This global estimate is somewhat lower than that of Hiç et al. (2016), who project waste of 850 kcal/capita/day by mid-century.

The changes in the relative shares within the pie show how the middle-income countries' contribution to global food waste has come to dominate this total. (It should be noted that the “share” here is a different concept than the SFW in the presented in Fig. 1) On the one hand, the high-income regions–population weighted–share of the 287 kcal (during 1992) was 57% and decreased 25 percentage points to reach 32% of the global 473 kcal wasted during 2013. On the other hand, China's share of global food waste increased from 5% during 1992 to 27% of the global total in 2013. These findings are consistent with previous studies estimating food waste via this caloric methodology (Hall et al., 2009; Hiç et al., 2016; Verma et al., 2020). The observed changes in relative contributions to the composite global daily caloric waste, leading to a dominant role of middle-income countries, follow from the rapid increases in population and income in developing countries where food comprises a large share of the average households' budget (Barrett and Dorosh, 1996); in contrast, the share of budget expended on food in developed countries such as US can be less

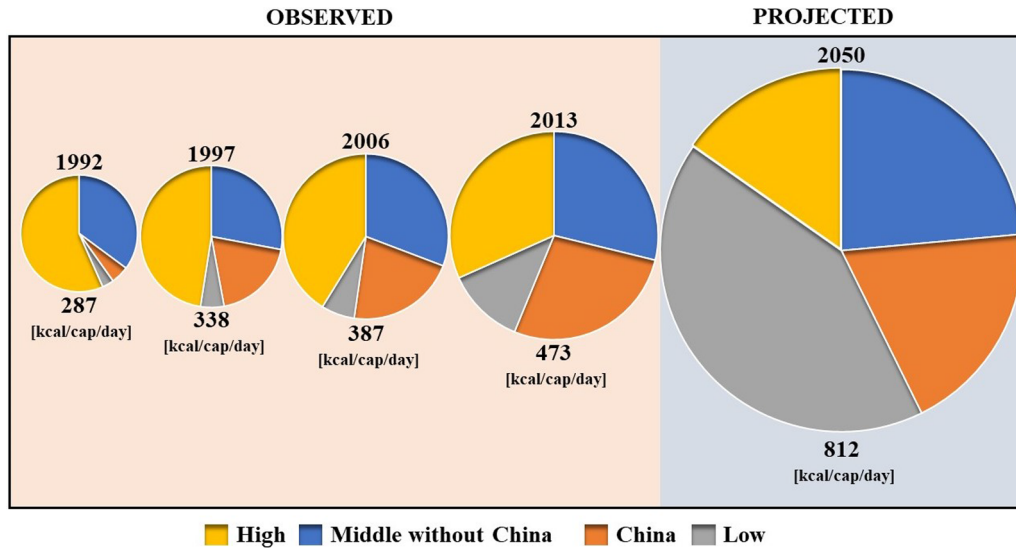


Fig. 2. Aggregates the food waste data from all 158 countries in our data set to the global level, showing the observed contribution of major country groupings to global, per capita food waste over the period 1992 to 2013 as well as our projections towards 2050 (see Section 5).

than 10% (US EPA, 2016). Additionally, we see that China plays a critical role in global food waste given its large population.

Having examined the historical evolution of food waste, we now turn to future projections. This will entail several steps: first estimating the relationship between food waste and income, then incorporating it into our economic model and finally making projections based on future growth in income, population, technology and food waste policies.

3.2. Estimating a model of food waste response to income growth

Given the apparent difference in behavior of *SFW* with respect to income growth amongst the low, middle and high income countries, we first test for structural breaks in our data set using the Chow test (Chow, 1960). Table 1 summarizes the results.² The large F statistic leads us to conclude that there are structural breaks in this relationship across the three income groupings, which suggests that we need to consider a non-linear functional form (see Appendix B) that allows for different responses of *SFW* to income at different income levels.

The type of non-linear relationship between the share of food waste in total food availability and per capita income suggested by Fig. 1 is evidenced in many social and economic processes. The response variable, in this case *SFW*, starts out rather flat, and at a low level. At low per capita income, food is relatively expensive and represents a large share of households' budgets (Barrett and Dorosh, 1996). They cannot afford to waste food and the opportunity cost of the time involved in food procurement, preparation and storage is relatively low (Lusk and Ellison, 2017). Furthermore, the nature of diets at low income levels – predominantly staples – is such that storage is easier. Food waste begins to grow as household incomes rise, diets diversify to include perishable fruits, vegetables and meats (Popkin, 1994), and wages rise, increasing the opportunity cost of time spent on food procurement and preparation (Lusk and Ellison, 2017). Increased away-from-home food consumption likely plays a role here as well as previous studies suggest that consumers are more likely to save food when eating at home when compared with eating away-from-home (Asioli et al., 2019). Fig. 1 shows that this acceleration is particularly striking as countries move into the

Table 1

Summary statistics and test for structural breaks.

	GDPpc	SFW
Observations	3466	3466
Mean	11,329	0.1243
Min	162	0.0001
Max	111,968	0.3698
Structural test	F (3, 3462) = 1081	Prob > F = 0

middle-income category. This growth in the overall share of food waste plateaus at high income levels when households have made the transition to a modern, industrialized economy. As consumers reach the affluent stage, a further increase of income would likely have no significant impact on calorie purchasing (including wasted calories). Rather, calorie purchases (including waste) are expected to enter a stage of stasis (Zhou and Yu, 2014).

The S-shaped curve suggested by Fig. 1 is quite similar to that found in the technology adoption literature where adoption rates start out slowly before reaching a 'take off' stage at which point the technology starts spreading at an increasing rate until it gradually levels off (Griliches, 1957; Jarvis, 1981). Usually these patterns of change in adoption rates are modelled through a logistic function (Nin et al., 2004; Ludena et al., 2007; Polson and Spencer, 1991). The logistic function has the advantage of being parsimonious, yet flexible enough to capture the essential features in these relationships, enabling the capture of convex as well as concave curvatures at different income levels. We find this flexibility essential to capture both the broad trends as well as the regional eccentricities (i.e., due to different regulations, cultural differences, and/or relative prices of food with respect to non-food items in the market) in the response on food waste as the income evolves. The logistic functional form used here postulates the following relationship between per capita income and *SFW*:

$$SFW_i = \frac{\gamma}{1 + e^{-\alpha - \beta * GDP_pc_i}} \quad (4)$$

The parameters γ , α , and β govern the shape of the logistic function. The value of β determines the speed of change in the function; a higher value implies a faster approach of *SFW* to the upper asymptote of the function γ . The parameter α governs the midpoint ascent, indirectly determining where the function starts to increase. After applying the standard logarithmic transformation, and including an *i.i.d.* error term, the estimating form of the equation becomes:

² Please find the Fig. A2 in Appendix B in which we illustrate the observed data points of Share of Food Waste (SFW) data across the income spectrum and the SFW projections obtained through the linear function estimation. That figure illustrates how a lineal approximation to model the relationship between income and food waste would over-project SFW for higher levels of income.

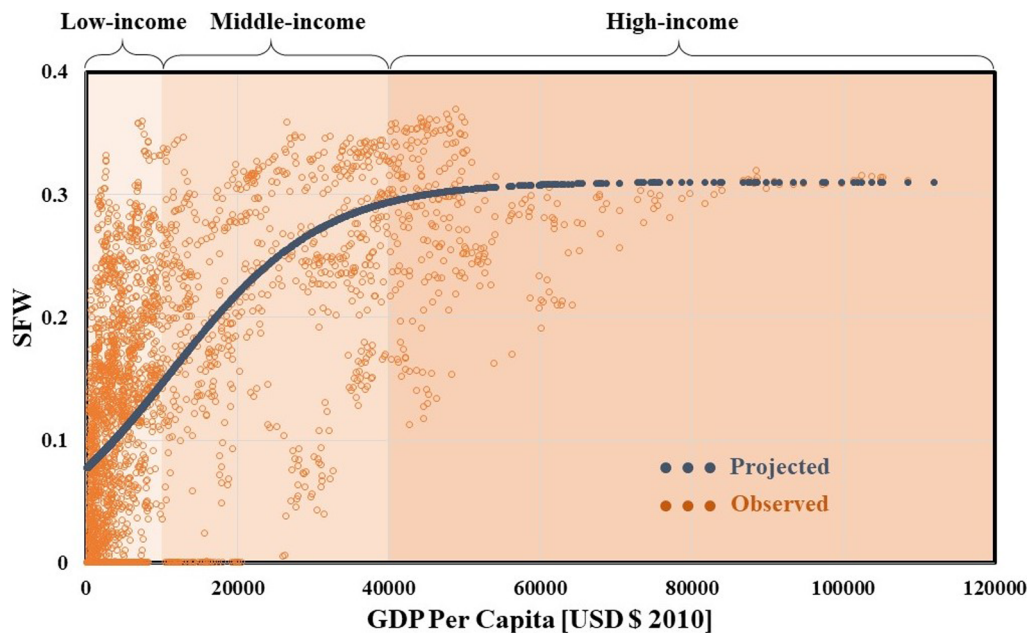


Fig. 3. The observed data points of Share of Food Waste (SFW) data across the income spectrum and the SFW projections obtained through the logistic function estimation described in Section 3.2.

$$Y_i = \log\left(\frac{SFW_i}{\gamma - SFW_i}\right) = \alpha + \beta * GDP_pc_i + \varepsilon_i \quad (5)$$

For a given value of γ , one may calculate the value of the left-hand side of the Eq. (4). Then α and β may be found by least-squares regression under the classical ordinary least squares (OLS) assumptions (Nin et al., 2004; Ludena et al., 2007). By iterating through this process, the value of γ may also be determined according to the criterion of minimizing the sum of squares of the residuals. There are several approaches for this, from systematic procedures to estimating the upper asymptote of the function such as the Golden Section Search and Fibonacci Search (Vardavas, 1989) to running numerous regressions, each with a different value for γ . Results from the latter procedure are reported in the table two. The confidence intervals of the two parameters estimated (α and β) show that these parameters are rather precisely estimated. These confidence intervals will also be employed when attaching error bars to our projections of future food waste.

Fig. 3 plots this estimated logistic function, along with the data points in our sample. As can be seen from that figure, while it seems that most countries follow this same general pattern of food waste as incomes rise, at any given income level SFW varies quite a bit. This is hardly surprising, as there are many other factors determining food waste beyond income (Chalak et al., 2016). These country-specific factors, as well as the economic modeling approach taken in Section 5 below, lead us to aggregate the data into regions and then re-calibrate the logistic function parameters to better reflect regional variation in the parameters governing Eq. (5).

3.3. Regional aggregation and calibration

In order to project future food waste, we aggregate countries to the regional level and then calibrate the regional parameters to reproduce our 2006 benchmark. While there is a cost to losing country-specific detail, this aggregation permits us to incorporate our projections of the share of food waste into a validated model of global partial equilibrium model of the agricultural sector. With this in hand we can project the level of food waste in 2050, as well as analyzing the consequences of alternative pathways for the reduction of future food waste. Regional

aggregation is also useful given the eccentricity of individual countries and potential reporting errors to the FAO. In anticipation of the economic projections to be undertaken in Section 5 below, we have chosen to aggregate countries to the geographic 15 regions in our economic model (Fig. 4). This allows to capture the changes in food waste through a large portion of the income spectrum over this period (see Appendix C for a compiled version of Fig. 4), while avoiding dealing with the inevitable country-specific eccentricities that arise in such a data set.

This particular aggregation into 15 regions has the additional advantage of matching with the global model SIMPLE³ which we use for future projections. Calibration involves adjusting the logistic function parameters for each region while requiring this function pass through the year 2006 benchmark data set used in Section 5 and based on FAO (FAO/WHO, 2017) and World Bank (World Bank, 2018) data. This calibration procedure minimizes the deviation across the entire series from the original estimates in Table 2 (illustrated in Fig. 3). We use the year 2006 as benchmark in anticipation of the economic projections to be undertaken in Section 5. Fig. 4 plots the aggregated regional data points, along with outputs from the region-specific logistic functions (i.e., projections) for each year over our sample period. The significant shifts in these functions across regions illustrates the importance of the calibration step for capturing regional variation in the share of food waste and matching observed data as well as undertaking global projections.

3.4. Future evolution of SFW

Fig. 5 puts these region-specific SFW functions in the context of a timeline starting in 1992 and continuing through the period of observation (up to 2013) and forward to 2050 using income projections to be discussed below. Error bars for the projected food waste shares were obtained through a bounding analysis using the lower and upper bounds from the confidence intervals in Table 2. From this figure, several points emerge. Firstly, the calibrated logistic functions now track individual regions' evolving food waste quite closely. Secondly, there is very little 'action' in the high-income countries, where the share

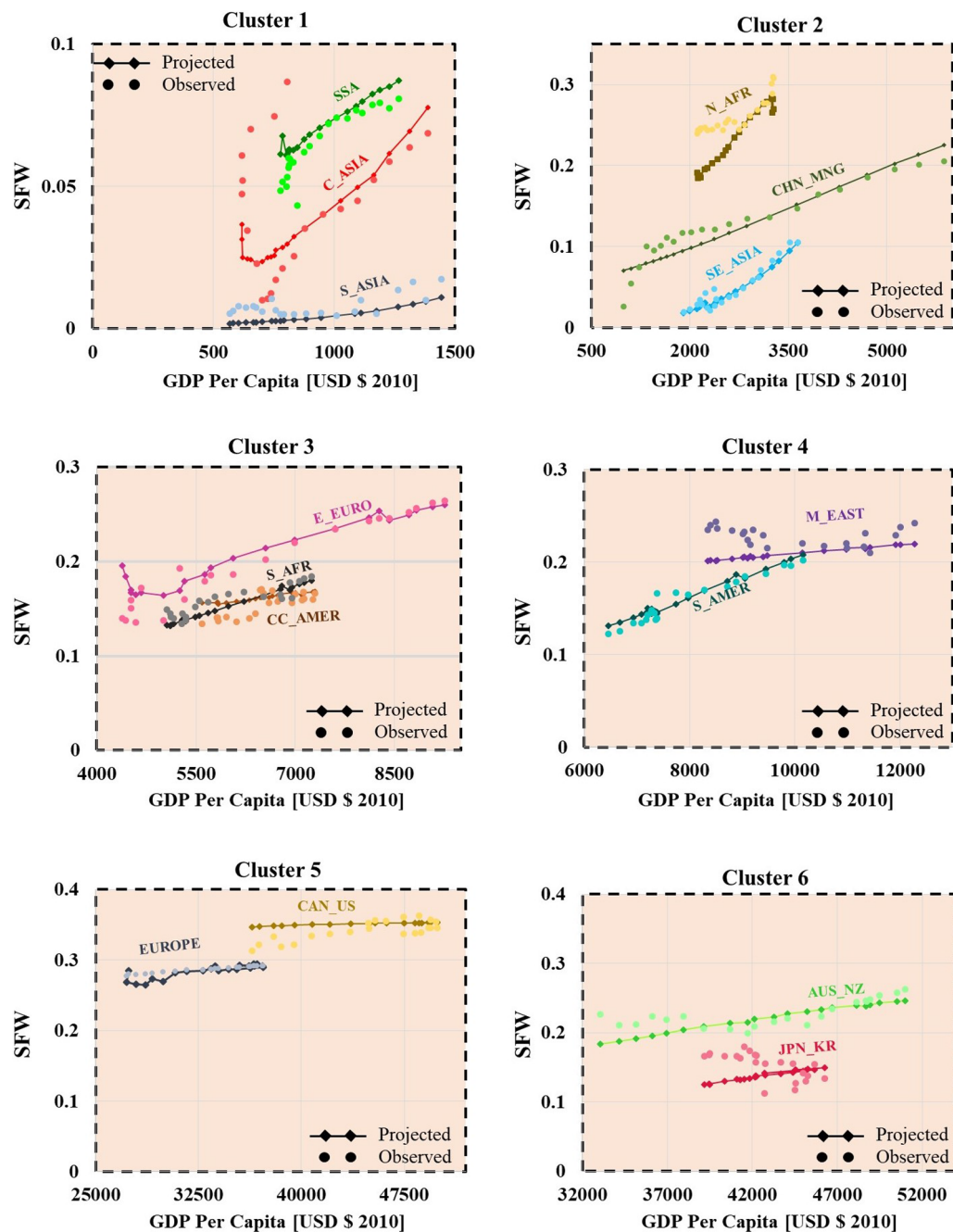


Fig. 4. The logistic function projections (points connected via the solid lines) and the observed levels of SFW collapsing the data points through weighted-population averages into 15 regions across the 22 annual data points (SFW & income for 1992–2013) for each region.

Table 2

OLS estimations for parameters in the logistic function.

	Coef.	[95% Conf. Interval]
α	-1.821084	[-1.873587 to 1.76858]
β	0.0000367	[0.0000341–0.0000393]
γ	0.3201	–

³ The Simplified International Model of Crop Prices, Land Use and the Environment (SIMPLE) model is a global partial equilibrium model of the agriculture sector. For a detailed explanation on the SIMPLE model, see the textbook by Hertel and Baldos (2016a, 2016b). The SIMPLE model is designed to capture the major socio-economic forces at work in determining food consumption (crops, livestock and processed foods), cropland use, output, prices

of food waste is not expected to change significantly in the absence of targeted policies. Thirdly, the most dramatic changes between 2013 and 2050 are expected in South Asia, where the economy is starting out at a very low level of food waste, but high-income growth over the next

(footnote continued)

and nutritional attainment. The SIMPLE model focuses on a few key relationships related to global agriculture, keeping it as simple as possible while capturing the important drivers of global agricultural change. In order to avoid frequent criticism of general or partial equilibrium models, identification problems when involving too many behavioral parameters since each estimation implies an error SIMPLE focuses only in the relationships that are considered essential. However, the authors acknowledge that there is a trade-off in this decision. With the risk of becoming too simple which might lead to introducing other errors.

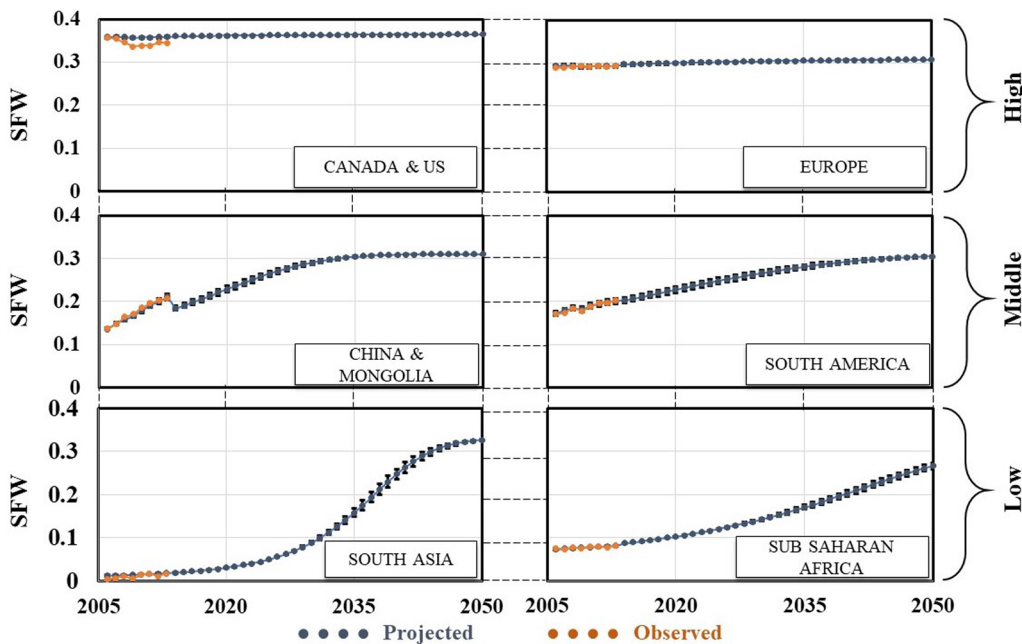


Fig. 5. SFW observed between 2006 and 2013 and projected towards 2050. The Fig. 5 includes 6 of the 15 regions in the study. The remaining figures are reported in the Appendix D. The top two panels present two high-income regions, the ones in the middle two middle-income regions and the two at the bottom present lower income regions (according to World Bank, 2018 classification of countries by income).

three decades is expected to boost *SFW* to nearly one-third. Finally, based on the error bars in Fig. 5, the most developed regions (US/Canada, Europe), already at a high level of *SFW*, as well as the middle-income ones (China and South America), present significantly less sensitivity to changes in the parameters shaping the function. However, the uncertainties in the projected calculations are greater in the low and lower middle-income regions (i.e., Sub Saharan Africa and South Asia) – particularly during the transition period to high income levels. It is also important to note that we base our projections in the observed values of food waste through the income spectrum. While the model attempts to capture the regional eccentricities, it does not capture changes in food waste beyond what has been observed in the period up to 2013 (e.g., potential decreases in food waste through increase of awareness). Below, we will explore the potential effects on resource use and food security of freezing the food waste (among other scenarios) in the results session.

4. Incorporating the SFW into a global partial equilibrium model of the agriculture sector

In order to convert the region-specific *SFW* functions reported in Table 2, into projections of global food waste, we require projections of income per capita and total food availability for each of the 15 regions. It is common in agricultural models to treat income as exogenous, and so we, too, adopt a partial equilibrium approach, taking income growth from other global modeling activities, while assuming limited feedback from food waste to national income. In an ideal world, we would have data on food waste by type of food commodity – i.e., a different *SFW* function for each food type. However, given the aggregate data set which we have been able to develop, we are forced to assume that the share of food waste in total availability is the same across all food types. This is clearly a limitation which should be relaxed in future work, as improved data become available.

Given this aggregate approach to food waste, we do not require an extremely detailed model of food consumption. Rather, we focus on obtaining accurate, long run projections of total food consumption and total calories available, by region. One partial equilibrium model suitable for such purposes is the SIMPLE model (a Simplified International Model of Prices, Land use and the Environment). It is attractive for our purposes since it has been subjected to historical validation with respect to long run evolution of crop output, prices, land use and caloric

undernutrition (Hertel and Baldos, 2016b; Baldos and Hertel, 2016, 2013, 2014).

The SIMPLE model includes three production activities in each of 15 regions: (1) an aggregate crop sector; (2) livestock; and (3) processed food, whereby the latter two utilize crop and non-crop inputs to produce food products for consumers. Food demand responds to changing prices and income through the incorporation of income and price elasticities which vary as a function of regional income per capita. These relationships are obtained from a cross-country analysis of purchasing patterns (Muhammad et al., 2011), and that vary by food commodity (crop, livestock, and processed foods).

The crops sector employs land and non-land inputs via a Constant Elasticity of Substitution (CES) production function and the use of inputs is governed by the extensive and intensive margins of factor supply. The crop commodity is a composite of all 175 crops in the FAOSTAT database, weighted by relative prices to produce output measured in corn-equivalent tons. Crops are traded internationally and consumed directly as well as indirectly through their use in livestock and processed food production. For a detailed exposition, see the textbook by Hertel and Baldos (2016a). The model is parsimonious and open source. As with our *SFW* data set, SIMPLE is based on FAO data.

5. Results

5.1. Model validation

As in Baldos and Hertel (2014) who used SIMPLE to examine changes in undernourishment over time, we start our analysis by evaluating how well the model projects *SFW* outcomes over an historical period, in this case, 2006–2013 (7-years). Often studies that use economic models to project future outcomes are not validated against history, yet this is a critical step. Additionally, this historical assessment provides valuable inputs for examining changes in the future. The historical projections in Fig. 6 are most accurate at the global level; the projections are less accurate at the regional level, which is consistent with previous studies attempting to validate global agricultural models (Baldos and Hertel, 2014; McCalla and Revoredo, 2001). Those authors find that food availability and price projections become less accurate with greater levels of disaggregation.

At the regional level, our framework underpredicts the growth in food waste in China, while over-predicting 2013 food waste in the US.

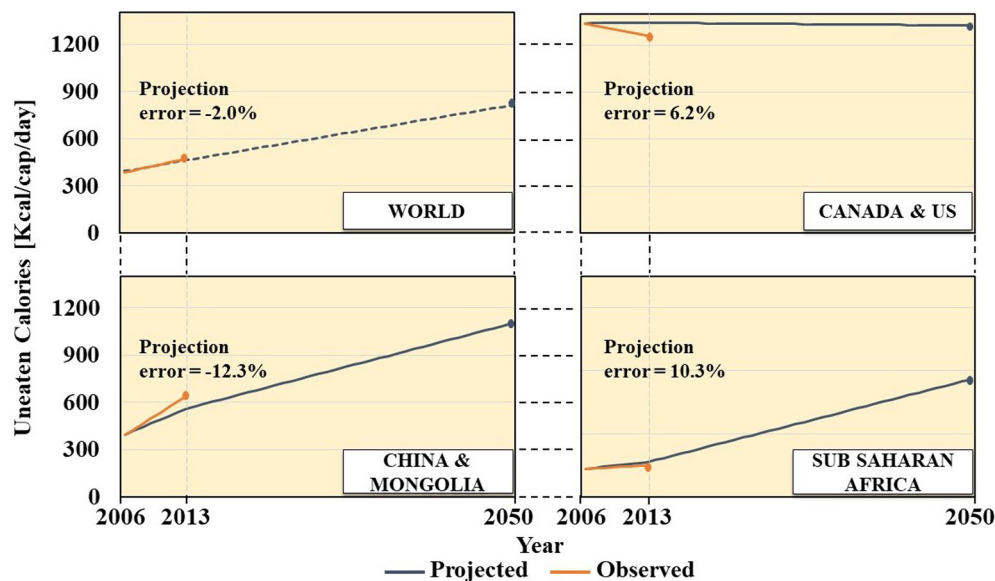


Fig. 6. Panels plot observed uneaten calories (kcal/cap/day) in 2006 and 2013, and model projections for 2013 and 2050 obtained from the baseline simulation starting in 2006. Projection errors (% difference between model projected and observed values for 2016) are reported.

Re-examining the US time series for SFW in Fig. 1, it can be seen that the food waste share jumped up around 2006 and then dropped to its level in the early 2000s by 2013. Our model is not capable of capturing this cyclical behavior. In the case of the low-income region in Fig. 6 – SSA, the model does reasonably well over the historical period, while anticipating a significant rise by 2050.

6. Future projections

6.1. Baseline

The projections of uneaten calories to 2050 in Fig. 6 rely on incorporation of Eq. (4) – albeit with the regionally calibrated parameters – into the SIMPLE model which produces estimates of total caloric availability and purchases. SIMPLE is projected forward with exogenous shocks to population, per capita incomes, total factor productivity (TFP) growth, and biofuel consumption. Growth rates for population and income were derived from the Shared Socioeconomic Pathways (Fricko et al., 2017). The Shared Socioeconomic Pathways (SSPs) create a framework for global studies, usually focused on environmental outcomes, to explore how the future can evolve under a consistent set of assumptions. They cover a wide range of hypothetical future states of the world by providing five different narratives. Here we use the SSP 2 as the reference in our baseline projections. Given its description of a “middle-of-the-road” state of nature, the SSP 2 is natural starting point to further explore integrated solutions for achieving societal objectives to reduce pressure on environmental resources (Fricko et al., 2017). In our projections, TFP growth rates are based on the historical estimates from Ludena et al. (2007) and Fuglie (2012). The growth in global biofuel consumption is from the document published in the World Energy Outlook (IEA, 2008, 2012) (shocks are reported in Appendix E Table A1. See Annex 1 for details; Ahmed et al., 2009; Gurgel et al., 2007; Harrison et al., 2000; Harrison and Pearson, 1996; Taheripour et al., 2007).

Fig. 7 reports projections for uneaten calories in 2013 and 2050, using our modeling framework. In the absence of significant policy interventions or behavioral changes, food waste is expected to increase substantially by 2050. Globally, SFW is expected to increase from 0.17 (17% of calories purchased are uneaten) to 0.26 in 2050. Daily uneaten calories are expected to nearly double going from 473 (kcal/cap/day) in 2013 to 812 (kcal/cap/day) in 2050. The largest per capita increases

in food waste are expected to arise in the emerging markets where population and income will likely increase most. This is consistent with Engel’s law, since is also expected that the share of budget expended on food would also be higher than in developing regions and the increasing purchases of food likely will lead to an increase in the excessive intake and waste of calories. In rich countries the SFW seems to have levelled off, so that middle income countries, particularly China and lower income regions as South Asia, South East Asia, and Sub Saharan Africa are expected to dominate future global food waste (see the rightmost pie chart in Fig. 2 – 2050). Note that China’s share of the global food waste declines from 2013 to 2050, as its food waste growth is outpaced by that of South and Central Asia, and Sub Saharan Africa.

6.2. Examining the consequences of alternative waste reduction pathways

In the light of these results, we turn our attention to the likely implications for land use and food security of curbing future trajectories of food waste, as well as examining their interactions with trade policies. We start by exploring the food security and land impacts of rolling back SFW in all regions, except for the poorest one – SSA, to 0.20 (SFW = 0.20 scenario).⁴ Our second experiment explores the impact of freezing SFW in all regions, except for SSA, at their values in 2020 (SFW = 2020 scenario). Finally, we consider the impact of a somewhat less stringent scenario wherein of the SFW freeze is not implemented until 2030 (SFW = 2030 scenario).

Each of these three experiments is undertaken against the backdrop of two different levels of global market integration (segmented vs. fully integrated markets) to shed light on the interactions of initiatives attempting to reduce food waste with trade policies. The different scenarios projected are the result of changing assumptions with respect to the future evolution of the global economy. The segmented markets specification is designed to reproduce current conditions, in which domestic agricultural markets are imperfectly linked to world markets due to domestic and border policies as well as trade and transport costs. The underlying idea in the segmented markets model is to reflect restricted accessibility to global markets. Not all consumers can buy goods in the global markets and not all producers are able to sell into the world market. The relative prices of domestic and international

⁴ From Fig. 5 we can see that SSA only rises above 0.20 at the end of the projected period.

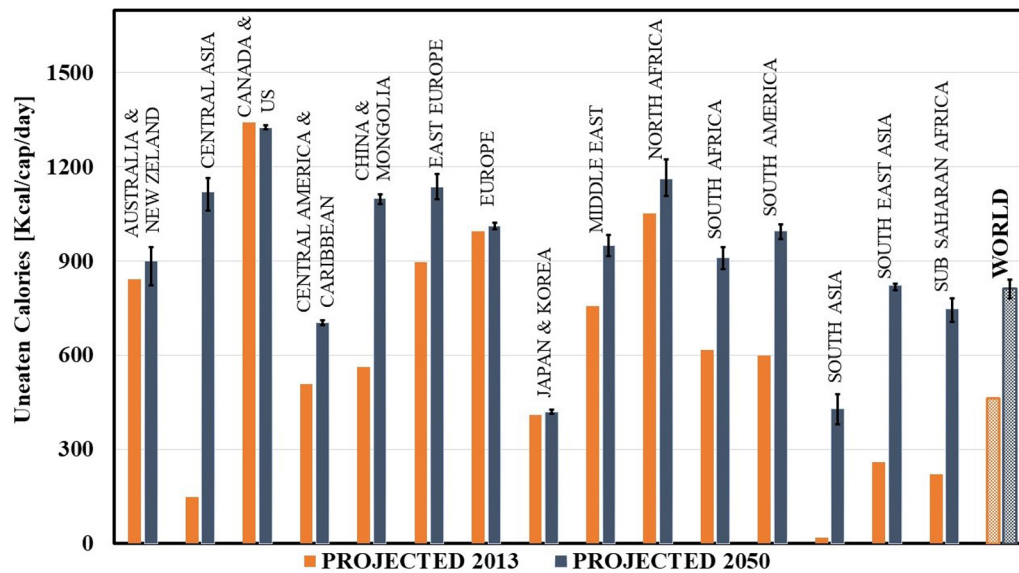


Fig. 7. Projected uneaten calories 2013 and towards 2050. Error bars were obtained following the same process described above in the document. The upper (lower) bound corresponds to the projected uneaten calories while using the upper (lower) bounds from the 95% CI for the region-specific α and β .

commodities, as well as the national market share of the domestically produced and of the international good, enter into a Constant Elasticity of Substitution demand function. Greater accessibility to global markets implies a larger elasticity of substitution between the domestic and international goods. This, in turn, results in less potential for deviation between local and international prices. When global market access is restricted for many households the implied elasticity of substitution is small and the potential for discrepancies between international and local prices is greater. The segmented markets version is also the specification used in the validation exercise described above and discussed in more detail in Hertel and Baldos (2016b). In contrast, the integrated markets version of the model assumes that all the consumers and producers can buy or sell in the global market, implying a unique equilibrium global price for crops. The integrated markets scenario is designed to reflect a future world in which global supply chains and enhanced trade infrastructure effectively remove barriers to trade and the world price and domestic price is equated for crop commodities.

Fig. 8 presents key results from these six experiments (three policies $\times$ two trade regimes). Results are reported as deviations from the 2050 baseline due to the three different food waste reduction scenarios. We focus here on the implications for global cropland use,

undernourishment headcount (in million, the quantity of people below the minimum caloric intake level for a healthy life), and prevalence of undernourishment (% of population whose caloric intake is below the minimum for a healthy life).

As expected, under all food waste scenarios global cropland area declines, as does undernourishment. However, even under the most extreme scenario ($SFW = 0.20$), the declines are rather modest as long as international markets are segmented. For example, the decline in cropland area in 2050 is less than 2%. This changes rather dramatically when international agricultural markets are assumed to be fully integrated. In this case, the decline in food demand in the rich countries is more fully transmitted across the globe, with stronger declines in land use and also in SSA undernourishment. (By mid-century, our projections suggest that this is where most of the world's remaining undernourishment will reside.) Therefore, we conclude that trade policies and food policies can be highly complementary, with greater trade integration enhancing the food and environmental benefits of reducing food waste.

Freezing the share of food waste at 2020 levels is nearly as effective as the across-the-board, 0.20 target. However, the $SFW = 2030$ scenario for freezing the share of food waste a decade later results in

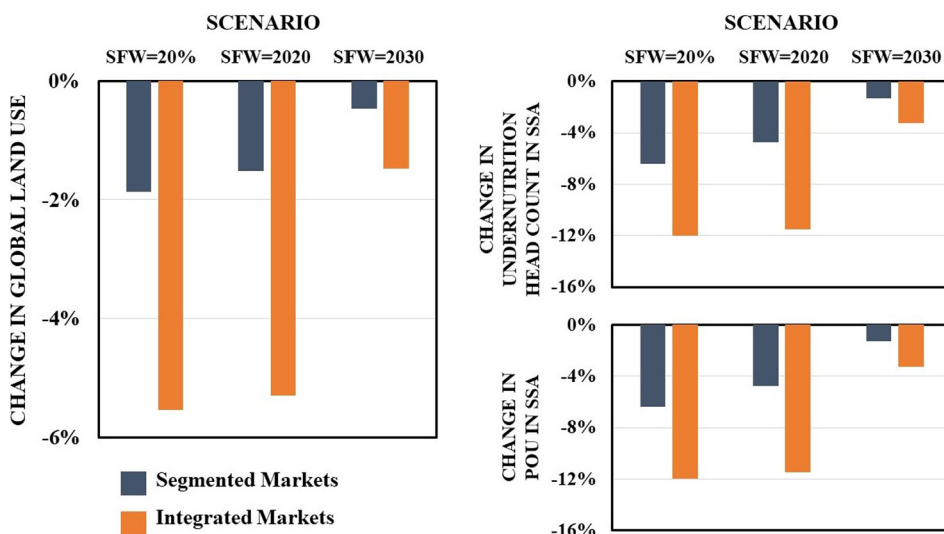


Fig. 8. The panel on the left reports the reduction on land use and the right panels report reductions in undernourishment headcount and in the prevalence of undernourishment (PoU) within SSA (% difference with respect to the baseline) resulting from limiting future trajectories on food waste (freezing SFW at 20%, 2020, and 2030 year's level) under different assumptions of market integration (segmented markets vs fully integrated international agricultural markets).

considerably lower impacts on the use of natural resources. This highlights the importance of moving quickly to limit the growth in food waste to the rate of growth of food availability. This must be done before the majority of the world's population begins exceeding the 0.20 threshold if this scenario is going to contribute to improved food and environmental security.

7. Discussion and limitations

The global pattern of food waste is evolving rapidly. There is an increasing gap between the average caloric supply and the average energy requirements. Under current trends, and in the absence of policy interventions or significant behavioral changes, we can expect that the global calories wasted at consumers level will nearly double by 2050. Per capita uneaten calories at the consumers level have leveled off in rich countries; however, this category is growing rapidly in middle income countries and it is these countries that will drive future global changes. By our estimates, China already dominates global food waste, but in the next three decades, it will be joined by South Asia and other lower income regions where rapid growth in food waste due to rising incomes, diversifying diets, and growing population could have a dramatic impact on the global total.

Previous studies have shown that mitigation of current levels of food waste offers one potential pathway for contributing to global environmental goals. Combined with other efforts, limiting food waste is an avenue to remaining within the planet's 'safe operating space' for land, water availability and quality & GHGs (Springmann et al., 2018). By modeling the evolution of food waste with per capita incomes, we are able to explore a richer set of (more realistic) scenarios than in previous studies which have typically abstracted from future growth in food waste (Springmann et al., 2018). We consider two cases wherein the share of food waste in food availability is frozen. Undertaking such a policy in 2020 would have a strong impact on global resource use and food security – particularly if accompanied by greater trade integration. However, if such measures are delayed until 2030, and if trade frictions lead to greater market segmentation, then this food waste mitigation pathway will likely have far more modest food and environmental security benefits.

More generally, the interaction between food waste reduction measures and trade policies is a novel contribution of this paper. Trade policies which increase agricultural market integration have the potential to amplify the benefits of food waste reductions for food security (by facilitating the accessibility to food in the most vulnerable regions) and for reduce pressure on natural resources.

Our study also highlights the importance of developing new measurement methods for food waste that can be rapidly deployed across the globe. Measurement is the foundation of international action and there is a need for approaches which can be readily implemented with existing data sources and incorporated into quantitative models to explore impacts and consequences of mitigation measures. The data base which we have developed builds on previous work in this area (Hall et al., 2009; Hiç et al., 2016; Verma et al., 2020) and represents another step in the direction of having a global, internationally comparable data set on food waste. However, more cross-validation of this approach with independent estimates (and ideally observations) of food waste is required.

In closing, there are some significant limitations to our analysis. First and foremost is the simplicity and level of aggregation of the model. SIMPLE does not attempt to capture all of the complexity

present in the global food economy (see Annex 1). The model also operates at a high level of aggregation, thereby abstracting from country-specific details that may be especially relevant from a policy perspective. The regional results are indicative of possible future outcomes at the country level but are no substitute for careful national analysis to inform country-level policies. Secondly, the long run relationship which we estimate between the share of food availability that is wasted and per capita income needs a more complete theoretical underpinning. Such a theory should also help to explain the wide variation in the share of food waste at a given income level. Also, there is a need for more detailed analysis of what types of food that are being wasted. Due to data limitations, we have been silent on this matter, simply working with a caloric aggregate. Commodity-specific food waste estimates would naturally lead to the use of a more detailed commodity market model of the global food system.

Finally, while we shed light on the potential benefits of curbing future trajectories of food waste focusing on limiting the expected increase in food waste in emerging economies, we do not analyze the potential costs related to efforts required to prevent food waste. Policy initiatives to prevent food waste encompass a wide range of instruments – from economic incentives (fees, taxes, and subsidies), to regulatory approaches (such as laws and standards, and/or mandatory management plans), to education/information campaigns, to solutions at retailers level (packaging, date-labelling, etc.). For an extensive literature review of these alternatives see (Schanes et al., 2018). Some of these policy instruments have been found to be successful in reducing food waste. Some examples are the use of economic incentives as weight-based fee systems in some developed countries; the use of regulatory approaches as the National Pact against Food Waste in France; and the education campaigns such as the “Love Food Hate Waste” lead by WRAP in the UK. However, most of these policies have been implemented in the context of developed economies. It may prove more challenging to implement these policies in the low-to middle income countries that are likely to account for most of the growth in food waste over the next three decades. Addressing the effectiveness and cost-benefit analyses of such instruments in the context of emerging economies is beyond the scope of this study. However, given the prominence of these economies in our projections of food waste, this is an important area for future research.

CRedit authorship contribution statement

Emiliano Lopez Barrera: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Funding acquisition. **Thomas Hertel:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Funding acquisition.

Acknowledgments

The authors thank Monika Verma for her early insights into food waste research and Russell Hillberry for his valuable feedback at early stages of the project. Two reviewers and the Guest Editor provided valuable comments on earlier drafts of this paper. LopezBarrera acknowledges funding under Purdue Collaboratory Systems Fellowship. Hertel acknowledges funding under USDA: USDA-AFRI grant number 2019-67023-29679 “Economic Foundations of Long Run Agricultural Sustainability” and USDA Hatch project 1003642.

Appendix A

The gap between supply and requirement of calories in the period 1975–2013 at global level (see Fig. A1).

The figure illustrates how globally the gap between the average energy supply at retailers/consumption level and the energy intake recommendations for an average person have sharply increased in recent decades. The energy supply is obtained from the FAO Food Balance Sheets. Energy requirements based on energy intake recommendations from WHO for an average person are calculated using global average demographics

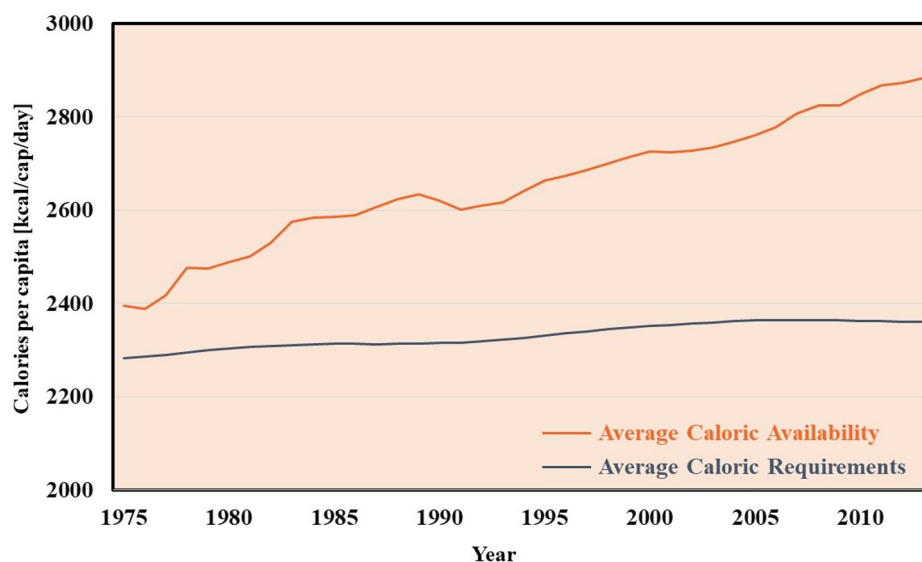


Fig. A1. The average caloric supply [kcal/cap/day] and the average energy requirements [kcal/cap/day] evolution through the time for the period 1975–2013 at a global level.

(age, weight, height, sex, physical activity level).

Appendix B

The linear model approximation (see Fig. A2).

The figure illustrates how a lineal approximation to model the relationship between income and food waste would over-project SFW for higher levels of income.

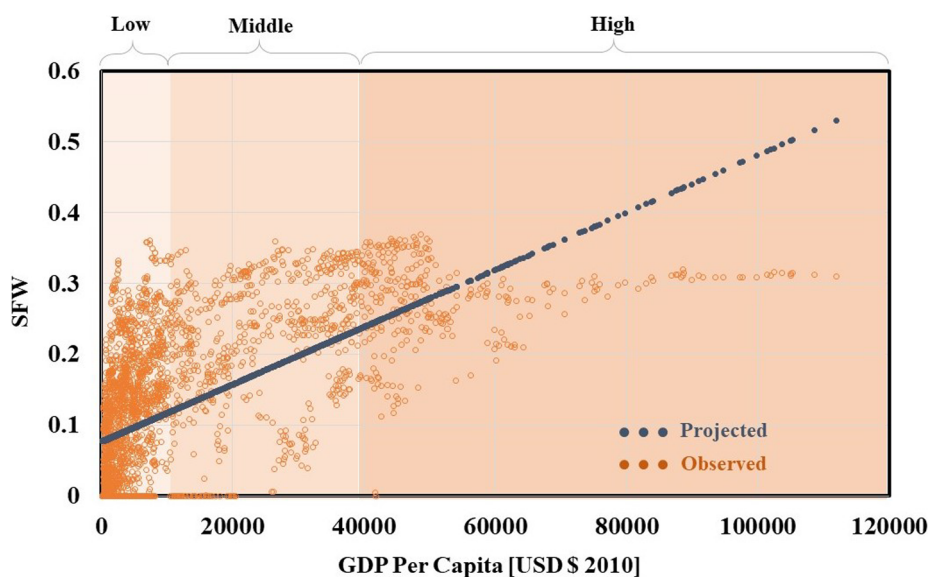


Fig. A2. The observed data points of Share of Food Waste (SFW) data across the income spectrum and the SFW projections obtained through the linear function estimation.

Appendix C

The logistic function projections and the observed levels of SFW (see Fig. A3).

This compiled version of the Fig. 4 collapsed into two panels allows to observe the response of food waste through the income spectrum.

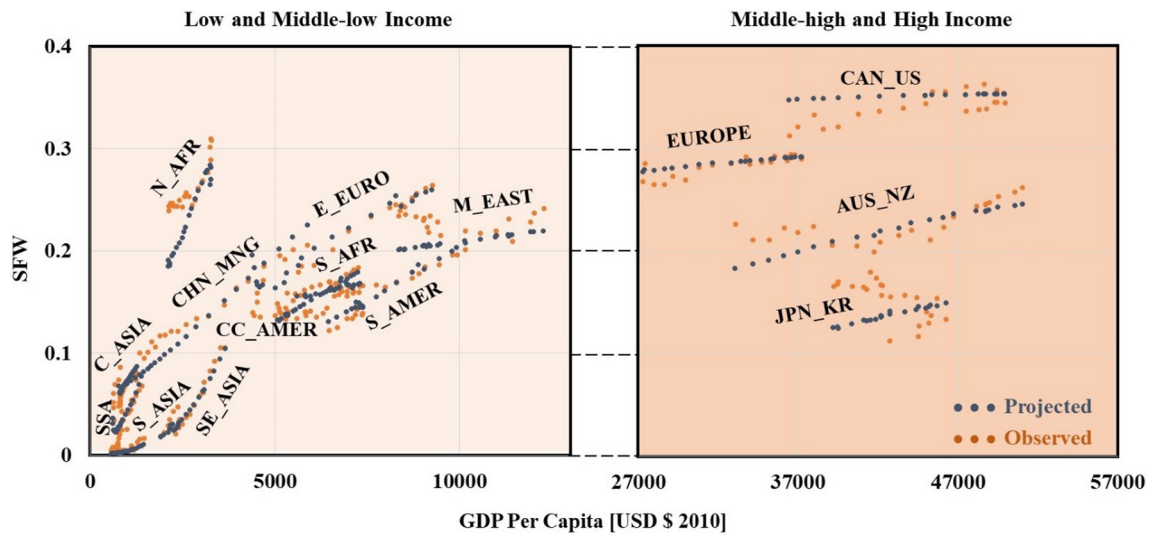
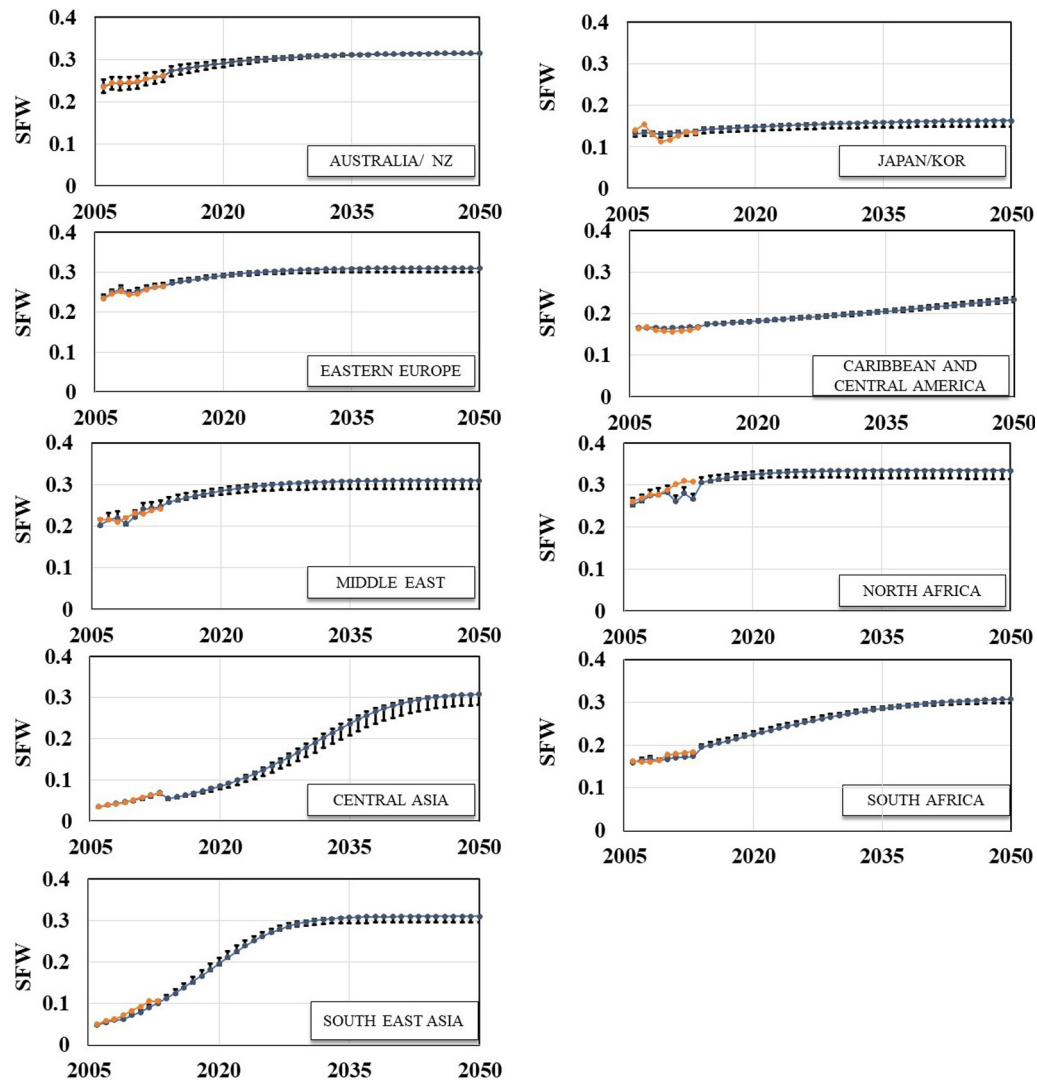


Fig. A3. The logistic function projections and the observed levels of SFW collapsing the data points through weighted-population averages 15 regions we obtain 22 annual data points (SFW & income for 1992–2013) for each region.

Appendix D

SFW observed between 2006 and 2013 and projected towards 2050



Appendix E

See Table A1.

Table A1

Assumed growth rates of exogenous variables (in % per annum rates).

Region	Population Annual rate	Per Capita Income Annual rate	Biofuels	TFP Annual rate
Eastern Europe	−0.35	3.23		1.45
North Africa	1.06	3.25		1.35
Sub Saharan Africa	2.46	4.43		0.69
South America	0.78	2.85		1.44
Australia/New Zealand	0.88	1.39		0.89
European Union	0.03	1.23		1.03
South Asia	0.99	5.70		0.84
Central America	0.98	2.37		1.43
Southern Africa	0.45	3.24		1.25
Southeast Asia	0.80	4.26		1.40
Canada/US	0.64	1.10		1.28
China/Mongolia	−0.13	5.77		1.75
Middle East	1.46	1.89		1.10
Japan/Korea	−0.39	1.74		1.40
Central Asia	1.18	4.72		1.45
World			6.96	

Sources: From left to right – Population and per capita Income growths from SSP2 (Fricko et al. 2017). The increase in demand for biofuels from IEA (2012, 2008). Future TFP growth rates from Ludena et al. (2007) using Fuglie (2012) as regional scalars.

Appendix F. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foodpol.2020.101874>.

References

- Abarca-Gómez, Leandra, Abdeen, Ziad A., Hamid, Zargar Abdul, Abu-Rmeileh, Niveen M., Acosta-Cazares, Benjamin, Acuin, Cecilia, Adams, Robert J., Aekplakorn, Wichai, Afsana, Kaosar, Aguilar-Salinas, Carlos A., 2017. Worldwide Trends in Body-Mass Index, Underweight, Overweight, and Obesity from 1975 to 2016: A Pooled Analysis of 2416 Population-Based Measurement Studies in 128·9 Million Children, Adolescents, and Adults. *The Lancet* 390 (10113), 2627–2642.
- Ahmed, S. Amer, Hertel, Thomas, Lubowski, Ruben, 2009. Calibration of a Land Cover Supply Function Using Transition Probabilities.
- Asioli, Daniele, Pinpart, Ponjan, Balcombe, Kelvin, 2019. Investigating Consumer Food Waste Decisions: A Cross-Country Comparison between Thailand and the United Kingdom.
- Baldos, U.L.C., Hertel, Thomas W., 2016. Global Food Security.
- Baldos, U.L.C., Hertel, T.W., 2013. Looking back to move forward on model validation: insights from a global model of agricultural land use. *Environ. Res. Lett.* 8 (3), 034024. <https://doi.org/10.1088/1748-9326/8/3/034024>.
- Baldos, Uris Lantz C., Hertel, Thomas W., 2014. Global food security in 2050: the role of agricultural productivity and climate change. *Australian J. Agric. Resour. Econ.* 58 (4), 554–570.
- Barrett, Christopher B., Dorosh, Paul A., 1996. Farmers' welfare and changing food prices: nonparametric evidence from rice in Madagascar. *Am. J. Agric. Econ.* 78 (3), 656–669.
- Bellemare, Marc F., Çakir, Metin, Peterson, Hikaru Hanawa, Novak, Lindsey, Rudi, Jeta, 2017. On the measurement of food waste. *Am. J. Agric. Econ.* 99 (5), 1148–1158.
- Britz, Wolfgang, Dudu, Hasan, Ferrari, Emanuele, 2014. "Economy-Wide Impacts of Food Waste Reduction: A General Equilibrium Approach."
- Carmona-Garcia, Gema, Leip, A., Weiss, F., Witzke, P., Verma, M., Philippidis, George, Kuiper, M.H., 2017. Deliverable No. D9. 4: Enhanced Modelling of Sustainable Food and Nutrition Security: The Agri-Food Commodity and Nutrient Flows and the Food Supply Chains. SUSFANS.
- Chalak, Ali, Abou-Daher, Chaza, Chaaban, Ja.d., Abiad, Mohamad G., 2016. The global economic and regulatory determinants of household food waste generation: a cross-country analysis. *Waste Manage.* 48, 418–422.
- Chow, Gregory C., 1960. Tests of equality between sets of coefficients in two linear regressions. *Econometrica: J. Economet. Soc.* 591–605.
- Defra, 2007. n.d. "Waste Strategy for England 2007," 127.
- FAO, 2013. Food Wastage Footprint: Impacts on Natural Resources : Summary Report. <http://site.ebrary.com/id/10815985>.
- FAO, 2015. Global Initiative on Food Loss and Waste Reduction, 8.
- FAO, 2019a. Key Differences between New and Old Food Balance Sheet (FBS) Methodology. FAO.
- FAO, 2019b. The State of Food Security and Nutrition in the World: Safeguarding against Economic Slowdowns and Downturns. <https://www.unicef.org/media/55921/file/SOFI-2019-full-report.pdf>.
- FAO/WHO, 2004. "Human Energy Requirements. Report of a Joint FAO/WHO/UNU Expert Consultation, Rome, 17-24 October 2001."
- FAO/WHO, 2017. "FAOSTAT." 2017. <http://www.fao.org/faostat/en/#data/FBS/metadata>.
- Fricko, Oliver, Havlik, Petr, Rogelj, Joeri, Klimont, Zbigniew, Gusti, Mykola, Johnson, Nils, Kolp, Peter, Strubegger, Manfred, Valin, Hugo, Amann, Markus, 2017. The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century. *Global Environ. Change* 42, 251–267.
- Fuglie, Keith, 2012. 16 Productivity growth and technology capital in the global agricultural economy. *Prod. Growth Agric.: Int. Perspect.* 335.
- Godfray, H. Charles J., Beddington, John R., Crute, Ian R., Haddad, Lawrence, Lawrence, David, Muir, James F., Pretty, Jules, Robinson, Sherman, Thomas, Sandy M., Toulmin, Camilla, 2010. Food security: the challenge of feeding 9 billion people. *Science* 327 (5967), 812. <https://doi.org/10.1126/science.1185383>.
- Griliches, Zvi, 1957. Hybrid corn: an exploration in the economics of technological change. *Econometrica, J. Econ. Soc.* 501–522.
- Gurgel, Angelo, Reilly, John M., Paltsev, Sergey, 2007. Potential land use implications of a global biofuels industry. *J. Agric. Food Indust. Organ.* 5 (2).
- Hall, Kevin D., Guo, Juen, Dore, Michael, Chow, Carson C., 2009. The progressive increase of food waste in America and its environmental impact. *PLoS ONE* 4 (11), e7940.
- Hall, Kevin D., Sacks, Gary, Chandramohan, Dhruva, Chow, Carson C., Claire Wang, Y., Gortmaker, Steven L., Swinburn, Boyd A., 2011. Quantification of the effect of energy imbalance on bodyweight. *The Lancet* 378 (9793), 826–837.
- Harrison, W. Jill, Horridge, J. Mark, Pearson, Ken R., 2000. Decomposing simulation results with respect to exogenous shocks. *Comput. Econ.* 15 (3), 227–249.
- Harrison, W. Jill, Pearson, Ken R., 1996. Computing solutions for large general equilibrium models using GEMPACK. *Comput. Econ.* 9 (2), 83–127.
- Hawkesworth, Sophie, Dangour, Alan D., Johnston, Deborah, Lock, Karen, Poole, Nigel, Rushton, Jonathan, Uauy, Ricardo, Waage, Jeff, 2010. Feeding the world healthily: the challenge of measuring the effects of agriculture on health. *Philos. Trans. R. Soc. B: Biol. Sci.* 365 (1554), 3083–3097.
- Hertel, Thomas W., Baldos, U.L.C., 2016a. Attaining food and environmental security in an era of globalization. *Global Environ. Change* 41 (November), 195–205. <https://doi.org/10.1016/j.gloenvcha.2016.10.006>.
- Hertel, T.W., Baldos, U.L.C., 2016b. Global Change and the Challenges of Sustainably Feeding a Growing Planet. Springer International Publishing, New York. <http://link.springer.com/10.1007/978-3-319-22662-0>.

- Hiç, Ceren, Pradhan, Prajal, Rybski, Diego, Kropp, Jürgen P., 2016. Food Surplus and Its Climate Burdens. *Environ. Sci. Technol.* 50 (8), 4269–4277.
- IEA, 2008. n.d. “World Energy Outlook 2008.” Text. World Energy Outlook. OECD Publishing. Accessed August 28, 2019. <https://www.oecd-ilibrary.org/content/publication/weo-2008-en>.
- IEA, 2012. n.d. “World Energy Outlook 2012.” Text. Accessed August 28, 2019. <https://www.oecd-ilibrary.org/content/publication/weo-2012-en>.
- Irfanoglu, Zeynep Burcu, Baldos, Uris Lantz, Hertel, Thomas, van der Mensbrugghe, Dominique. 2014. Impacts of Reducing Global Food Loss and Waste on Food Security, Trade, GHG Emissions and Land Use.
- Jarvis, Lovell S., 1981. Predicting the diffusion of improved pastures in Uruguay. *Am. J. Agric. Econ.* 63 (3), 495–502.
- Kummu, Matti, De Moel, Hans, Porkka, Miina, Siebert, Stefan, Varis, Olli, Ward, Philip J., 2012. Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Sci. Total Environ.* 438, 477–489.
- Lipinski, Brian, Hanson, Craig, Lomax, James, Kitinaja, Lisa, Waite, Richard, Searchinger, Tim, 2013. Reducing Food Loss and Waste. World Resources Institute Working Paper, pp. 1–40.
- Ludena, Carlos E., Hertel, Thomas W., Preckel, Paul V., Foster, Kenneth, Nin, Alejandro, 2007. Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts. *Agric. Econ.* 37 (1), 1–17.
- Lusk, Jayson L., Ellison, Brenna, 2017. A note on modelling household food waste behaviour. *Appl. Econ. Lett.* 24 (16), 1199–1202.
- McCalla, Alex F., Revoredo, Cesar L., 2001. Prospects for global food security: a critical appraisal of past projections and predictions. *Intl. Food Policy Res. Inst.* 35.
- Muhammad, Andrew, Seale, James L., Meade, Birgitm, Regmi, Anita, 2011. International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data. USDA-ERS Technical Bulletin, no. 1929.
- Monier, V., Mudgal, S., Escalon, V., O'Connor, C., Gibon, T., Anderson, G., Morton, G., 2010. Preparatory Study on Food Waste across EU 27. European Commission, Directorate-General for the Environment.
- Nin, Alejandro, Hertel, Thomas W., Foster, Kenneth, Rae, Allan, 2004. Productivity growth, catching-up and uncertainty in China's meat trade. *Agric. Econ.* 31 (1), 1–16.
- Parfitt, Julian, Barthel, Mark, Macnaughton, Sarah, 2010. Food waste within food supply chains: quantification and potential for change to 2050. *Philos. Trans. R. Soc. B: Biol. Sci.* 365 (1554), 3065–3081.
- Polson, Rudolph A., Spencer, Dunstan S.C., 1991. The technology adoption process in subsistence agriculture: the case of Cassava in Southwestern Nigeria. *Agric. Syst.* 36 (1), 65–78.
- Popkin, Barry M., 1994. The nutrition transition in low-income countries: an emerging crisis. *Nutr. Rev.* 52 (9), 285–298.
- Reisch, Lucia, Eberle, Ulrike, Lorek, Sylvia, 2013. Sustainable food consumption: an overview of contemporary issues and policies. *Sustain.: Sci., Practice Policy* 9 (2), 7–25.
- Risk, N.C.D., Collaboration, Factor, 2016. A century of trends in adult human height. *Elife* 5, e13410.
- Schanes, Karin, Dobernig, Karin, Gözet, Burcu, 2018. Food waste matters - a systematic review of household food waste practices and their policy implications. *J. Cleaner Prod.* 182 (May), 978–991. <https://doi.org/10.1016/j.jclepro.2018.02.030>.
- Springmann, Marco, Clark, Michael, Mason-D'Croz, Daniel, Wiebe, Keith, Bodirsky, Benjamin Leon, Lassaletta, Luis, de Vries, Wim, Vermeulen, Sonja J., Herrero, Mario, Carlson, Kimberly M., 2018. Options for keeping the food system within environmental limits. *Nature* 562 (7728), 519.
- Svedberg, Peter, 1999. 841 million undernourished? *World Dev.* 27 (12), 2081–2098. [https://doi.org/10.1016/S0305-750X\(99\)00102-3](https://doi.org/10.1016/S0305-750X(99)00102-3).
- Taheripour, Farzad, Birur, Dileep, Hertel, Thomas, Tyner, Wally, 2007. “Introducing Liquid Biofuels into the GTAP Data Base.”
- Thyberg, Krista L., Tonjes, David J., Gurevitch, Jessica, 2015. Quantification of food waste disposal in the United States: a meta-analysis. *Environ. Sci. Technol.* 49 (24), 13946–13953.
- US EPA, OLEM. 2016. “United States 2030 Food Loss and Waste Reduction Goal.” Overviews and Factsheets. US EPA. April 14, 2016. <https://www.epa.gov/sustainable-management-food/united-states-2030-food-loss-and-waste-reduction-goal>.
- Vardavas, Ilias Mihail, 1989. A fibonacci search technique for model parameter selection. *Ecol. Model.* 48 (1–2), 65–81.
- Verma, Monika, de Vreede, Linda, Achterbosch, Thom, Rutten, Martine M., 2020. Consumers discard a lot more food than widely believed: estimates of global food waste using an energy gap approach and affluence elasticity of food waste. *PLoS ONE* 15 (2), e0228369.
- Verma, Monika, Linda de Vreede, M., Rutten, M., Achterbosch, T.J., 2017. Consumer Food Waste: New Estimates and Approach Inferring Consumption Food Waste from Private Expenditure.
- World Bank, 2018. “World Bank Open Data | Data.” 2018. <https://data.worldbank.org/>.
- Xue, Li, Liu, Gang, Parfitt, Julian, Liu, Xiaojie, Van Herpen, Erica, Stenmarck, Åsa, O'Connor, Clementine, Östergren, Karin, Cheng, Shengkui, 2017. Missing food, missing data? A critical review of global food losses and food waste data. *Environ. Sci. Technol.* 51 (12), 6618–6633.
- Zhou, De, Yu, Xiaohua, 2014. Calorie elasticities with income dynamics: evidence from the literature. *Appl. Econ. Perspect. Policy* 37 (4), 575–601.