GLOBAL FOOD SYSTEMS: ADDRESSING MALNUTRITION THROUGH SUSTAINABLE SYSTEM PATHWAYS

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Abstract

Addressing malnutrition (in all its forms) whilst developing a global food system compatible with environmental sustainability remains one of the most pressing challenges of the 21st century. The current framing of our food systems fails to fully capture the inequities in production, distribution, efficiency and sufficiency of all components necessary to end malnutrition. This research presents a holistic, scalable and replicable framework to model food system pathways (across all essential nutritional components, including macronutrients, micronutrients and amino acids), providing quantification of production, losses, allocation and conversions at all stages of the value chain. Furthermore, this framework attempts to translate current food metrics—often presented in tonnage or absolute terms—into daily per capita figures to provide important context for how this translates into food security and nutrition. This framework can be applied at global, regional and national levels.

Here, this model is first presented at a global level and then focuses on India as a national-level example. Results highlight that, at a global level, we produce the equivalent of 5800 kilocalories and 170 grams of protein per person per day through crops alone. However, major system inefficiencies mean that less than half of crop calories and protein are delivered (or converted) for final food supply. Pathway inefficiencies are even more acute for micronutrients; more than 60% of all essential micronutrients assessed in this study are lost between production and consumer-available phases of the food supply system. Globally we find very large inequalities in per capita levels of food production, ranging from 19,000 kilocalories (729 grams of protein) per person per day in North America to 3300 kilocalories (80 grams of protein) in Africa. Large variations are also seen in terms of food system efficiency, ranging from 15-20% in North America to 80-90% in Africa. Understanding regional inefficiencies, inequalities and trade imbalances will be crucial to meet the needs of a growing global population. This case is exemplified in India-specific framework results. India's domestic production capacity would result in severe malnutrition across a large proportion (>60%) of the population (even under ambitious yield and waste reduction scenarios) in 2030/50. This shortfall will have to be addressed through optimised intervention and trade developments.

This work also explores a number of solutions which couple improved nutritional outcomes with sustainability. Analyses of global and national nutritional guidelines conclude that most are incompatible with climate targets; the recommended USA or Australian diet provides minimal emissions savings relative to the business-as-usual diet in 2050. Low-cost, high-quality protein will remain a crucial element in developing an effective and sustainable food system. This research explores the potential of two sources. Results find that meat substitute products have significant

health and emission benefits, but are strongly sensitive to both price and consumer acceptability. The environmental impact of aquaculture is strongly species-dependent. This study provides the first quantification of global greenhouse gas emissions from aquaculture, estimated to be 227±61 $MtCO_2e$ (approximately 3-4% of total livestock emissions). This is projected to increase to 365±99$MtCO_2e$ by 2030.

Acknowledgements

A PhD is often considered to be a solitary endeavour; however, a number of people have supported this journey along the way. They deserve more than the words which follow can capture.

Firstly I would like to thank the UK Natural Environmental Research Council (NERC); this project was funded through its Doctoral Training Programme (DTP). Without this financial support, this thesis would not have been possible.

Supervisors can make or break a student's PhD experience; I could not have asked for more from mine. My most sincere thanks go to Professor Dave Reay, and Professor Pete Higgins for their continued support, encouragement and guidance throughout this journey. Their contributions extend far beyond that of PhD supervision: they have evolved into key academic, teaching and life mentors. From them I have developed invaluable skills, perspectives and insights which I will carry throughout the rest of my career. Both encapsulate the type of person I aspire to be. Thank you for the opportunity to begin this journey—I'm proud of what we have achieved, and hope I can live up to your example in the years which follow.

I am a strong believer in looking beyond one's research to consider how it fits and interacts with the bigger picture. I have been lucky to have had the chance to work on a number of projects alongside my PhD which have allowed me to do this. I owe a huge thanks to Max Roser and Esteban Ortiz-Ospina from Our World in Data (University of Oxford) who provided me with the opportunity to explore how my work fits within the broader development context. I have already learned so much from you both. I am excited to see all that we can achieve in the years to follow. I am also grateful to the team at *3f bio*; this research attempts to provide insights into both the challenges and potential solutions to global malnutrition and sustainability. I hope our work can translate some of these solutions into reality.

Finally, and most importantly, my thanks go to my family for all of their love and support. The PhD journey starts far in advance of a proposal or acceptance letter; it is the culmination of a lifetime of curiosity, questioning and exploration. All my thanks go to my parents, who have forever provided a home within which these qualities could be nurtured and kept alight. At the heart of this thesis lies the principle of equality: that we deserve to live in a world where no one gets left behind. This is not a belief I was born with, but one I learnt from you. This thesis is therefore dedicated to you.

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General Introduction

The world is currently failing to develop an inclusive, sustainable food system. This is true across all three parameters of sustainability - environmental, social and economic. The United Nations (UN) defines achieving a sustainable food system as "a dynamic process in which achieving food and nutrition security today should also contribute to food and nutrition security for future generations." (United Nations 2015)

This - in line with the more general Bruntland definition of sustainability (Bruntland 1987) - poses two challenges: ensure adequate nutrition (which is defined by an appropriate balance of all macro and micronutrients) for all today, in a way which is environmentally sustainable to ensure future generations (and other species) also have the opportunity to do so. If we are to develop a sustainable food system, and in doing so address several of the UN's Sustainable Development Goals (SDGs) (United Nations, 2016), then solutions must address both of these elements. Failure in one, by definition, fails to meet our sustainability goal.

Looking at this global challenge through a single lens - one focused solely on food security, or one solely on environmental protection – is therefore likely to be inadequate. Meeting global nutritional requirements would be simplified without critical underlying concern for resource and environmental pressures. Conversely, the environmental impacts of our food system would be minimised through reduced agricultural production, resource requirements, and as a result, widespread undernourishment. The fundamental challenge therefore lies in the ability to couple these end goals: to ensure nutritional wellbeing for all in a way that maximises environmental sustainability.

The UN notes that such ambition can only be achieved through the implementation of a system-based approach (United Nations 2015). Indeed, food systems are complex, not only from a resource and supply chain perspective, but from the interactions these have with economic, social, nutritional, and institutional factors.

The need for a holistic approach to this reconciliation between these, sometimes conflicting outcomes, underlies the motivation and approach to this thesis. This work comprises seven research chapters, all of which have been written in the form of (and submitted) for academic publication. This collection of chapters can be broadly defined in terms of two distinct, but interconnected sections.

Part One (which incorporates the first four chapters) attempts to build and present a holistic, reproducible, and scalable framework for the quantification of global, regional or national food systems. The first step in building sustainable food systems involves understanding how our current systems operate: this incorporates the stages of production, trade, allocation, livestock conversion, wastage, processing, and availability for final consumption. Not only is a holistic understanding of food pathways from 'field-to-fork' crucial, but also a reframing of the manner in which we quantify these pathways. The framework outlined and applied within these chapters attempts to give full coverage to all crucial elements of nutrition – this extends conventional analyses beyond tonnage or caloric terms to all macronutrients, micronutrients and amino acids. A developed understanding of the form, efficiency and relative importance of supply chain stages at global, regional and national levels is essential if we are to work towards more effective and optimal food delivery systems. This quantification allows us to identify the key hotspots within these pathways, and the potential of particular interventions along the value chain to improve food security, nutritional availability, and reduce environmental impact.

Where Part One attempts to capture the status, inequalities and inefficiencies of our food system today (in other words, the challenges we face in coupling our social and environmental sustainability goals), Part Two attempts to explore some of the potential solutions to these issues. Solutions can come in various forms, whether through legislation, market factors, health and sustainability guidelines, and changing social norms.

In the three chapters of Part Two, I explore the role of global and national dietary guidelines to assess whether the current 'un-sustainability' of our food system is solely driven by overconsumption, or whether our current nutritional recommendations are also incompatible with our environmental goals. A clear outcome from my analyses in Part One is that protein – and in particular animal protein – represents an important dietary inequity, and is a fundamental driver of the inefficiency and environmental impact of our value chain pathways. The final two chapters of this thesis therefore explore the role that alternative high-quality protein sources of meat substitutes, and aquaculture can play in developing a more efficient and equitable food system.

The outcomes of the seven chapters which follow converge upon a key message: if we are to couple our ambitions of ending malnutrition for all, and doing so in a way which is environmentally sustainable, we need to transform the way we view, approach and manage our food systems at the global and national levels. This need for transformation extends from the agricultural production and pre-harvest stage through to the consumer. The first step in rethinking the way we develop these pathways is to understand the state of the current system. Only then can we identify the points across the value chain which need to be addressed, and the potential of particular solutions or interventions to optimise or transform them. It is hoped that the work which follows provides a valuable contribution in changing the way we think about our food systems, and what can be done to ensure they work for everyone.

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Part One

Part One of this thesis comprises of four chapters/papers focused on developing and applying a holistic framework for the assessment of global, regional and national-level food systems.

One of the main goals of this framework is to change the way we measure, report and discuss levels of food production and availability. Currently, the standard metric—and that reported by the UN Food and Agricultural Organization—for reporting of agricultural production, trade, and wastage is total annual mass terms, such as million tonnes of wheat per year (http://www.fao.org/faostat/en/) .

There are three fundamental issues with understanding and communicating such metrics: commodity tonnage provides little indication of nutritional value; reporting in absolute terms provides minimal understanding of the sufficiency of production levels relative to population numbers (and the adequacy of such in a growing population); and the differences in nutritional composition of commodities (for example, one tonne of soybeans is not equivalent to one tonne of barley) makes comparisons of crop allocations difficult. The insufficiency of our current metrics for assessing agricultural production and food systems has recently received attention within the academic literature (Sukhdev et al. 2016), however extensive quantification and application of such principles is still lacking.

The frameworks presented in the chapters which follow aim to correct these food metrics in two fundamental ways: they normalise all metrics to an average daily per capita value; and redefine commodity statistics from mass terms to the essential nutritional components of macronutrients, micronutrients and amino acids. Whilst the literature features multiple studies which discuss food systems in caloric (and sometimes protein) terms (Alexander et al. 2017; Foley et al. 2011; Bajželj et al. 2014), there are no studies I am aware of which feature such evaluations across all of the nutritional components necessary for human health.

The analyses reported in the following studies rely heavily on the UN FAO's Food Balance Sheets (FBS) which provide global, regional and national level data on commodities at all stages of the value chain from agricultural production, through trade, feed, seed, non-food uses, losses, wastage, processing & distribution, to final consumer availability (http://www.fao.org/faostat/en/). Whilst the best—and only—source of complete data coverage for the full value chain for every country, FBS has notable limitations. The UN acknowledges these statistics are not perfect; poor data coverage and reporting in some cases requires interpolation and extrapolation by experts within the FAO (FAO 2001). Furthermore, FBS data extend only to the country-level, and therefore fail to capture the often significant differences in production, supply chains and food availability at state, district or local levels.

As a result, the following analyses are not designed or appropriate for use in the evaluation of household-level intervention, such as dietary supplementation or nutritional intervention. The best source for the evaluation of these specific needs remains household survey data. Household survey data, however, also have important limitations. Understanding household-level food access or intake tells us little about the efficiency of our food systems, the magnitude of losses across the value chain, the potential for increased food availability through particular supply chain interventions, or projected future food availability as demographics and resource capacities change. To perform these analyses (as I do in the following chapters) a holistic and complete outlook on the 'field-to-fork' pathways is essential.

The following work therefore provides a preliminary framework based on the best available (yet imperfect) data. Improved data coverage, confidence and availability across the value chain are critical if such analyses are to continue to develop. The novelty of this framework lies in its replicability: whilst this work focuses on quantification at the global level, and its scalability to India (as an example) at the country-level, its methodology can be reproduced for any country. India was selected as an exemplar at the national level for several reasons, including its already prevalent malnutrition challenges; continued population growth in the coming decades; strong domestic reliance on agricultural production; and economically-driven dietary transitions.

If we are to effectively transform the global food system in a way that sustainably works for everyone, understanding its current situation is an essential place to start.

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Chapter One:
Feeding the world: a 50-year analysis of regional and national food system efficiency

After article: Ritchie, H, Reay, D, Higgins P. Feeding the world: a 50 year analysis of regional and national food system efficiency. Nature Sustainability (submitted). As appears in Chapter One.

Abstract

Globally we face increasing challenges to not only feed—but adequately to nourish—a growing population whilst reducing overall environmental impact. This is essential if the world is to meet its Sustainable Development Goal targets by 2030. Improving the efficiency of our current food systems will be crucial to achieving this. Here, for the first time, we map the total food system efficiency at global, regional and national levels from 1961-2013. Globally (where daily per capita production was 5,800 kilocalories and 171 grams of protein) we find large inequalities in per capita levels of production, ranging from 19,000 kilocalories (729 grams of protein) per day in North America to 3,300 kilocalories (80 grams of protein) in Africa. Large variations are also seen in terms of food system efficiency; less than half of the world's calories and protein is delivered (or converted via livestock) to final food consumption, ranging from 15-20% in North America to 80-90% in Africa.

Food systems are facing increasing pressure to meet the needs of a growing—and transitioning—global population (International Food Policy Research Institute, 2016). In 2016, the total number of people defined as undernourished (as defined by a persistent inadequate caloric intake) increased to 815 million—one of the first years to show an increase in recent decades (FAO, 2017c). The United Nations Food and Agricultural Organization (FAO) projects that, under business-as-usual progress, the world will fail to meet the second Sustainable Development Goal (SDG) of 'zero hunger', with 653 million people still undernourished by 2030 (FAO, 2017b). This estimate also fails to capture the broad ambition of SDG2 of ending all forms of malnutrition, meaning the eradication of protein and micronutrient deficiencies, which are even more prevalent than caloric insufficiency (Haddad *et al.*, 2016; International Food Policy Research Institute, 2016).

The global food system also faces severe resource and ecological pressures, driven by both population growth, and more importantly the evolution of economically-driven resource-intensive dietary habits (Tilman and Clark, 2014). Accounting for approximately one-quarter of greenhouse gas emissions, 33 percent of soil degradation, 60 percent of terrestrial biodiversity loss, and 70 percent of global freshwater withdrawals, the development of a more sustainable agricultural system is arguably one of humankind's greatest challenges in the 21st century (Ingram *et al.*, 2016; FAO, 2017b).

Globally, total food production is far in excess of caloric requirements for our current population (Alexander *et al.*, 2017) and is theoretically sufficient to meet the needs of a 9.8 billion population in 2050. However, the FAO reports that a 60-70 percent increase in food production is actually required by mid-century; driven by inequity of access, an increasing global population and increased diversion of food crops towards alternative uses such as animal feed and industrial uses (Alexandratos and Bruinsma, 2012). Such requirements are also likely to be antagonistic with sectoral decarbonisation and wider ecological targets (Bajželj *et al.*, 2014).

Improvements in food system efficiency—that is, improved efficiency of delivery of food 'from field-to-fork'—are crucial if global nutrition and sustainability targets are to be simultaneously addressed (Foley *et al.*, 2011). Whilst there is a reasonable understanding of the caloric efficiency of the food system at the global level (Alexander *et al.*, 2017), how this varies geographically and how this has changed with time is poorly understood. As food systems become increasingly globalised, an understanding of how system efficiencies have varied and currently vary across the world could play an important role in modelling and projecting relative future potential for improvement.

Here, for the first time, we have attempted to quantify food system efficiencies—in terms of both calories and protein—at the global, national and regional (by five regions of North America, South America, Europe, Africa and Asia) level from 1961 to 2013 (the current full-range extent of FAO data). This quantification is shown across several key metrics: the level of caloric and protein primary crop production (prior to value chain losses and inefficiencies) as measured on an average per capita basis for the given population; *domestic* average per capita levels after correction for global trade; the efficiency of the national or regional food system in delivering food from the production to final food supply level; and the efficiency of the system from domestic supply (post-trade) in delivering to the food supply level.

This quantification has been carried out by utilising UN FAO Food Balance Sheet (FBS) data on crop production, domestic supply quantity and final food supply quantity. All are reported on a commodity-specific mass basis (FAO, no date). Combining crop mass balance data with commodity-specific composition figures (i.e. caloric and protein content per unit mass) (FAO, 2001) we provide estimates of total caloric and protein availability from the production, domestic supply, and final food supply stages (see Methods). Whilst imperfect in quantification of the total global food system, the FAO FBS provide the only historical large-scale data source for holistic analysis of global, regional and national commodity pathways from production to final consumer availability. It therefore provides useful insights on the scale and relative comparison of food system efficiencies over the last 50 years.

We do not attempt to relate or infer production, domestic supply and final food supply figures to levels of undernourishment, however we have normalised caloric and protein figures to an average daily per capita metric at the global, national and regional levels using annual UN population estimates (United Nations: Department of Social and Economic Affairs, 2013). This correction for population is essential to enable comparison both geographically (between countries and regions) and temporally (to measure how production and efficiency measures have changed with time).

Calorie and protein crop production

Calorie and protein crop production is here measured as the total caloric (or protein) contained in primary crop production, measured in average daily per capita terms (kilocalories or grams of protein pppd).

Figures 1a-b summarise regional and national level results of caloric production; with protein production results in Figures 1c-d. This is shown as time-series trends from 1961-2013 at regional levels, and global maps of national-level estimates from 2013, the latest year of published FAO balances.

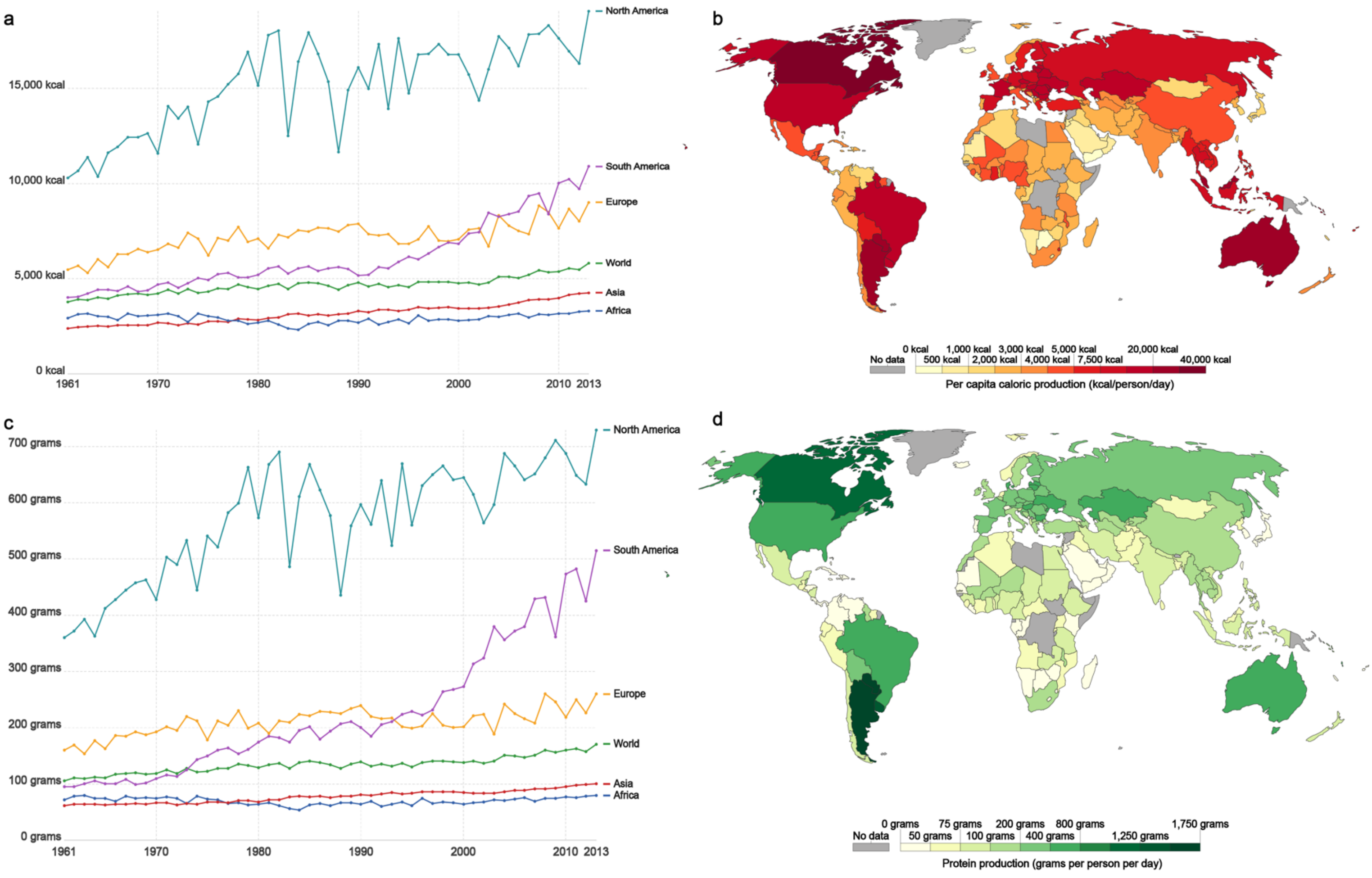

Figure 1a-d: Primary crop caloric and protein production by region and country. Primary crop calorie production in average per capita terms: (a) by region from 1961 to 2013, in kcal pppd; and (b) by country in 2013 in kcal pppd. Primary crop protein production in average per capita terms: (c) by region from 1961 to 2013, in grams pppd; and (d) by country in 2013 in grams pppd.

Time-series data in Figure 1a show changes in regional caloric production over the last half-century (with 2013 data summarised in Table 1). Despite a rapidly growing population, global caloric crop production has increased from 3775 kilocalories per person per day (kcal pppd) in 1961 to 5812 kcal pppd in 2013—more than double the global average daily energy requirement (ADER) in 2013 of 2358 kcal pppd (FAO, 2017a).

Region	**Caloric production (kilocalories per person per day)**	**Protein production (grams per person per day)**	**Caloric production system efficiency**	**Protein production system efficiency**
World	5812	171	49.6%	47.4%
Africa	3309	80	79.3%	87.0%
Asia	4267	100	65.1%	77.5%
Europe	9022	260	37.3%	39.3%
North America	19,062	729	19.2%	15.0%
South America	10,896	515	27.8%	16.7%

Table 1: Global and regional estimates of caloric and protein crop production, and system efficiencies (2013). Average per capita caloric and protein production in crops by region, measured in kilocalories per person per day and grams per person per day, respectively. Also detailed are production system efficiencies measured as the ratio of crop caloric and protein production to final food supply in 2013.

Regionally and temporally, we find large variations in production. Caloric production in 2013 was lowest in Africa—rapid population growth combined with poor and stagnating yields have limited increases in per capita caloric production, increasing from only 2916 to 3309 kcal pppd from 1961 to 2013 (Dzanku, Jirstrom and Marstorp, 2015). Although falling below global average per capita production levels, rapid agricultural development and productivity gains in Asia (Evenson and Gollin, 2003) have increased production from 2375 to 4267 kcal pppd over this period.

North America attains the highest levels of production, nearly doubling from 10,289 to 19,062 kcal pppd between 1961 and 2013. South America has seen the largest growth, increasing modestly by from 4036 to 5174 kcal pppd from 1961 to 1990 before more than doubling to 10,896 kcal pppd^{-1} over the last 20 years. A combination of productivity gains and land extensification in soybean production (predominantly for animal feed) (Masuda and Goldsmith, 2009) and sugar cane for biofuel production (Balat and Balat, 2009) have been suggested as primary drivers of this increase in crop output. Caloric production in Europe has also maintained modest growth over the last 50 years, increasing from 5483 to 9022 kcal pppd.

Figure 1b presents caloric production data at a national level in 2013 (full results for all countries for all metrics dating 1961-2013 are provided in Supplementary File 1). Overall, national-level production was typically in-line with regional-level trends, with per capita output lowest in Sub-Saharan Africa, followed by Asia. With a relatively low population density and high agricultural productivity (Veeman and Gray, 2010), Canada achieved the highest per capita calorie production at 30,687 kcal pppd in 2013. In the same year Argentina, Paraguay, Malaysia and Australia complete the top-five global producers, with outputs of 29,297; 25,466; 21,259; and 20,299 kcal pppd, respectively.

The overall regional patterns of *Pp* and trade were similar to that of calories—these are shown in Figures 1c-d and summarised in Table 1. At a global level, crop protein production averaged 171 grams pppd^{-1}. For reference, the World Health Organization (WHO) recommends a minimum protein intake level of 0.83 grams per kilogram of body mass in adults—this results in a minimum intake of 50 grams per day for an average 60 kilogram individual (WHO/FAO/UNU Expert Consultation, 2007). Primary protein production was therefore several multiples higher than global requirements.

Regionally there is large variation in production. At the lower end, Africa produced 80 g pppd^{-1} in 2013, followed by Asia (100 g pppd); Europe (260 g pppd^{-1}); South America (515 g pppd); and North America, which produced 729 g pppd—an order of magnitude higher than nutritional requirements. Although per capita protein production has increased in all regions (although only marginally in Africa), growth in recent decades has been highest in South America, increasing 2.5-fold since 1990.

Production system efficiencies

Production system efficiency is defined as the percentage of calories (or protein) produced at the crop level which is available (or converted via livestock) at the final food supply stage. For national and regional efficiencies, this is measured based on domestic food supply availability per capita.

Food system inefficiencies arise in various forms. Food losses and wastage, whether in the agricultural production or post-harvest stages, is a clear inefficiency. If the definition of efficiency is based on the ratio of primary crop production to final *food* supply, then crop allocations to industrial uses, including biofuels, also fall into this category. Energy conversion in the livestock production process can have low efficiency, with, for example energy conversion ratios as low as 2-3% for beef production (Shepon *et al.*, 2016). As a result, food crop allocation to animal feed can also be considered a system inefficiency. Note that figures of final food supply in our calculations include both plant and animal-based products, so outputs of the livestock conversion process are included.

There are two additional inefficiencies which our analyses here do not capture. Firstly, our calculations are based on final food supply; that is, average per capita food available for consumers. This is not necessarily reflective of actual consumption, as wastage at the consumer level is not captured. Furthermore, our final food supply figures measure caloric availability rather than energy requirements. Overconsumption (a growing health and nutrition issue (Haddad *et al.*, 2016)) may therefore also be considered a system inefficiency (if our food system is to deliver adequate nutrition for all) (Alexander and Moran, 2017). Therefore, our results will likely underestimate the complete system inefficiency, with larger underestimation in high-income countries which typically have high consumer food wastage (FAO, 2011) and dietary overconsumption (FAO, no date) relative to those with lower incomes.

Figures 2a-b show levels of caloric production system efficiencies by region from 1961-2013, and at national levels in 2013. Regional results are also summarised in Table 1, with full country-level results provided in Supplementary File 1. Production system efficiencies can exceed 100% for countries which are large net importers of food—for example, South Korea and Japan had efficiencies of 244% and 217%, respectively due to a strong dependence on food imports (Chang, Lee and Hsu, 2013).

At a global level in 2013, approximately half of the world's crop calories produced were available (or effectively converted into animal products) for final human consumption. This represents an 8% reduction in efficiency from 1961 when the global caloric system efficiency was 58%.

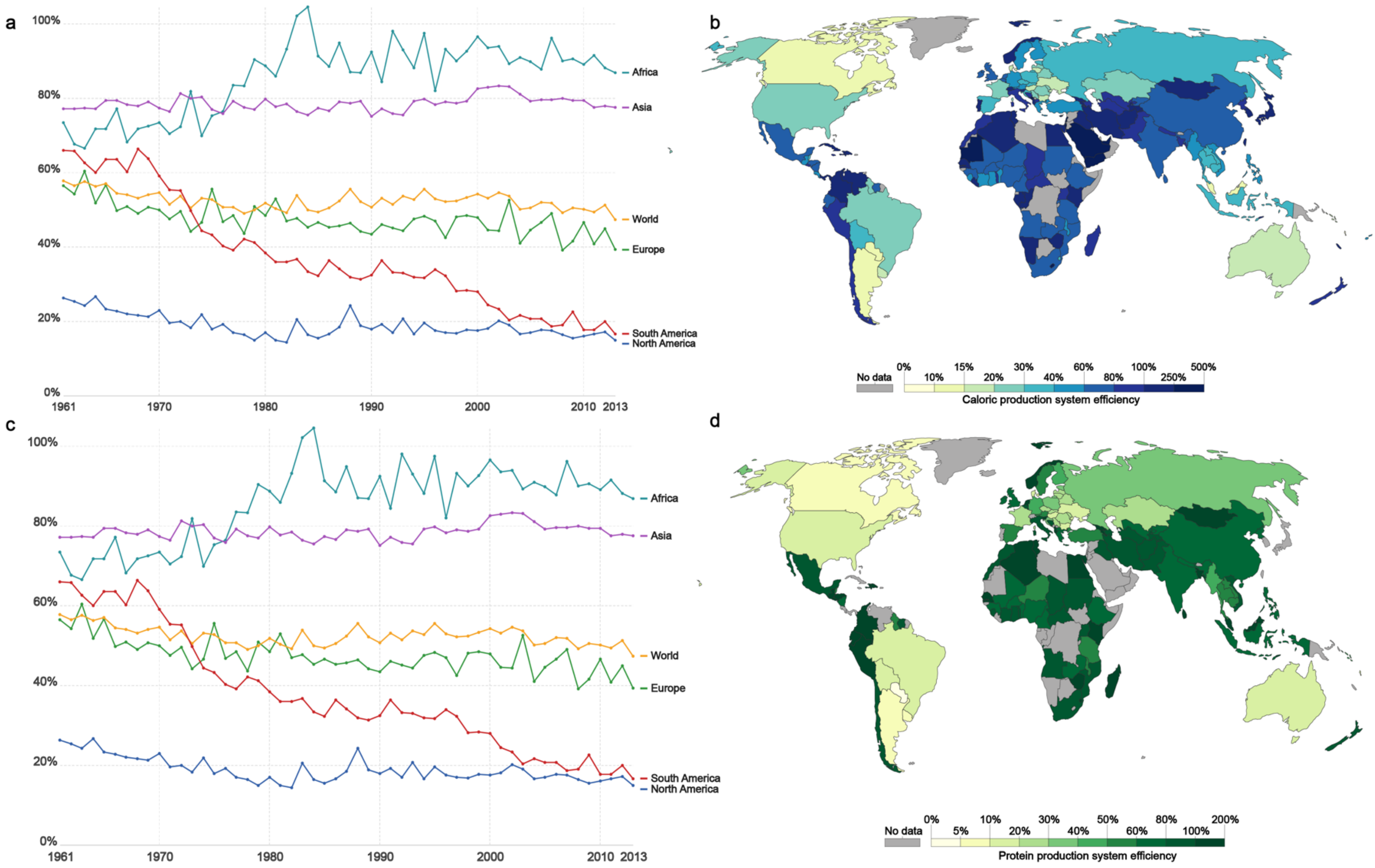

Figure 2a-d: Caloric and protein production system efficiencies by region and country. Caloric production system efficiency (the percentage of crop calories produced which are delivered or converted into final food supply), (a) by region from 1961 to 2013; and (b) by country in 2013. Protein production system efficiency (the percentage of crop protein produced which are delivered or converted into final food supply), (c) by region from 1961 to 2013; and (d) by country in 2013.

Regional patterns provide much larger variation, both spatially and temporally. North America had the lowest production system efficiency, with only 19% (down from 28% in 1961) of caloric production available for domestic final consumption. North America's high inefficiencies predominantly arise from its large allocation of crops to animal feed and biofuel production. The United States is the world's largest beef and poultry producer, and second largest pigmeat producer (FAO, no date). North America as a whole also accounted for almost half (45%) of global biofuel production in 2013 (BP, 2016).

Crop production for animal feed and biofuel production had similar impacts on food system inefficiency in South America. In 2013, only 28% of crop calories produced were available for domestic food consumption. In 1990 this figure was 51%, meaning its efficiency has nearly halved over the last two decades.

Between 37 and 38% of Europe's crop calories were available for human consumption in 2013—down from 55% in 1961. Over this period, Europe's meat production doubled from approximately 30 million to 60 million tonnes per year (FAO, no date), whilst its share of global biofuel production grew from less than 1% in 1990 to 17% in 2013 (BP, 2016).

Relative to the Americas and Europe, production system efficiency in Africa and Asia was high, at 79% (three to four times the efficiency in the Americas) and 64%, respectively. Since Africa produces only 5-6% of global meat products (FAO, no date) and a negligible proportion of first generation biofuels (BP, 2016), the majority of its inefficiency is likely to be a result of post-harvest losses (FAO, 2011). Although still relatively high, Asia's production system efficiency had declined from 76% in 1961. Asia's meat production—largely driven by rapid growth in China—increased more than 15-fold over this period, and accounted for 43% of global meat products in 2013 (FAO, no date). Since Asian biofuel output is relatively low, this rapid expansion of its livestock sector is likely to be the primary driver of its efficiency decline.

Protein production system efficiencies are shown in Figures 2c-d. Production system efficiencies overall follow a similar pattern to that of calories. Globally, approximately 48% of crop protein production is effectively delivered (or converted via livestock) as final food supply for consumption. This is 1-2% lower than for calories, but again approximates to half of all protein being lost across the system.

Regionally, protein production system efficiency was lowest in North and South America, with only 15% and 17% respectively available for domestic human consumption at the end of the supply chain. Protein efficiency in the Americas—in particular in South America—was notably lower than that of calories. This is likely to be a result of South America's dominance in protein-rich soybean production for animal feed, and global exports. Europe's protein efficiency was comparable to its caloric efficiency, at 39-40% in 2013.

Africa's protein production system efficiency was notably higher than its caloric efficiency, at 87% in 2013. Asia's protein production system efficiency was also notably higher than for calories, at 78% in 2013.

Trade-adjusted caloric and protein supply

The food system is highly globalised—food security and provision is therefore tightly aligned to how food supplies are traded. Here we define domestic crop availability, as primary crop production adjusted for trade (i.e. primary production minus exports, plus imports and corrected for stock changes). This is also measured in average daily per capita terms (kilocalories or grams of protein pppd).

Figures 3a-b (as a time-series by region, and global map by country in 2013) present results on domestic caloric crop availability—that is, production figures corrected for imports, exports and stocks (i.e. domestic supply quantity after trade). Regions or countries where domestic caloric availability was lower than caloric production correspond to their being a *net exporter* of crop calories, whereas regions or countries with higher domestic calories are *net importers*. This regional comparison is also detailed in Table 2.

Region	Domestic caloric supply (kilocalories per person per day)	Domestic protein supply (grams per person per day)	Domestic caloric system efficiency	Domestic protein system efficiency
World	5737	169	50.3%	48.0%
Africa	4045	98	64.9%	70.7%
Asia	4713	130	59.0%	59.5%
Europe	8890	258	37.9%	39.5%
North America	14,433	326	25.4%	22.4%
South America	7409	486	40.9%	26.4%

Table 2: Global and regional estimates of caloric and protein production, and system efficiencies after correction for trade (2013). Average per capita domestic caloric and protein supply in crops by region, measured in kilocalories, and grams of protein per person per day after correction for crop imports, exports and stocks. Also detailed are domestic supply system efficiencies measured as ratio of trade-adjusted crop caloric and protein supplies to final food supply in 2013.

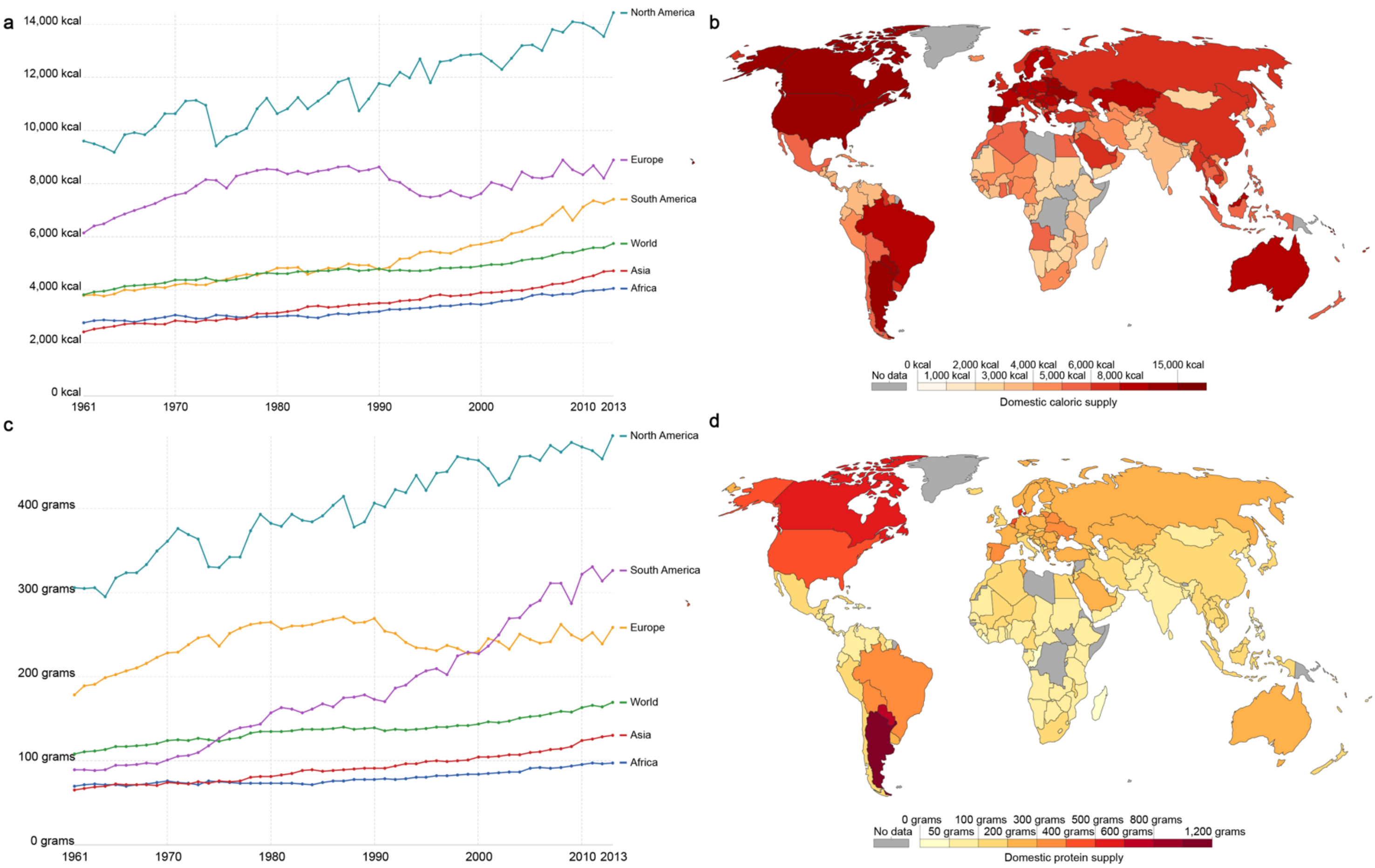

Figure 3a-d: Trade-adjusted (domestic) crop calorie and protein supply by region and country. Trade-adjusted (domestic) crop calorie production in average per capita terms: (a) by region from 1961 to 2013, in kcal pppd; and (b) by country in 2013 in kcal pppd. Primary crop protein production in average per capita terms: (c) by region from 1961 to 2013, in grams pppd; and (d) by country in 2013 in grams pppd.

Regionally we see that North and South America were both net exporters (exporting 24% and 32% of calories respectively); Asia and Africa were net importers (importing 10% and 22% of calories respectively); whilst Europe's imports and exports approximately balance. At a national level, all of the world's largest per capita producers exported more than half of their caloric production. Note that the small variation in global figures between caloric crop production and 'domestic' crop availability represent the calories stored as stocks.

Full country-level data from 1961-2013 are also provided in Supplementary File 1. After correcting for trade, Denmark had the world's largest domestic crop caloric availability, totalling 18,945 kcal pppd in 2013, owing to a combination of high agricultural productivity, a dominant farming sector and large share of food-based exports (Danish Agriculture & Food Council, 2014). Canada had the second largest domestic supply with 14,946 kcal pppd –less than 50% of its production values. Brazil, the United States, Argentina, Paraguay and Uruguay were the five largest soybean exporters in 2013 (FAO, no date), resulting in large reductions in domestic supply relative to primary production.

At the lower end of the spectrum, several countries across Sub-Saharan Africa, including Botswana, the Central African Republic, Uganda and Kenya, had domestic crop supplies below 2500 kcal pppd in 2013.

Protein supply adjusted for trade (domestic crop protein availability) typically reflects the trends seen in caloric terms. Protein figures at regional and national levels are presented in Figures 3c-d; Table 2; and full country-level values in Supplementary File 1. Africa and Asia remained net protein importers; North and South America net exporters (with North America exporting more than half of its crop protein); and Europe approximately balancing protein imports and exports.

Trade-adjusted production (domestic availability) system efficiencies

Domestic system efficiency is here defined as the percentage of domestic crop food supply (crop production adjusted for trade) which is available (or converted via livestock) at the final food supply stage. This is measured as the efficiency for both calories and protein.

Figure 4a-b summarises domestic system efficiency in caloric terms at regional and national levels. Global and regional level results are also provided in Table 2, with full country-level figures in the Supplementary Data.

Since North America was a large net exporter of calories, its efficiency metric increases once trade is adjusted for; in 2013, 25% of crop calories available as domestic supply were available (or converted) for final consumption. Crop production for exported animal feed had similar impacts on food system inefficiency in South America. Since South America produces and exports more than half of global soybean crops (FAO, no date), its overall food system efficiency in 2013 increased to 41% (up from 28% without trade adjustments) when adjusted for trade.

As Europe's imports and exports of crop calories effectively balance, trade adjustments make a negligible difference to food system efficiencies. In 2013, 38% of Europe's domestic crop calories were available for human consumption in 2013—down from 55% in 1961.

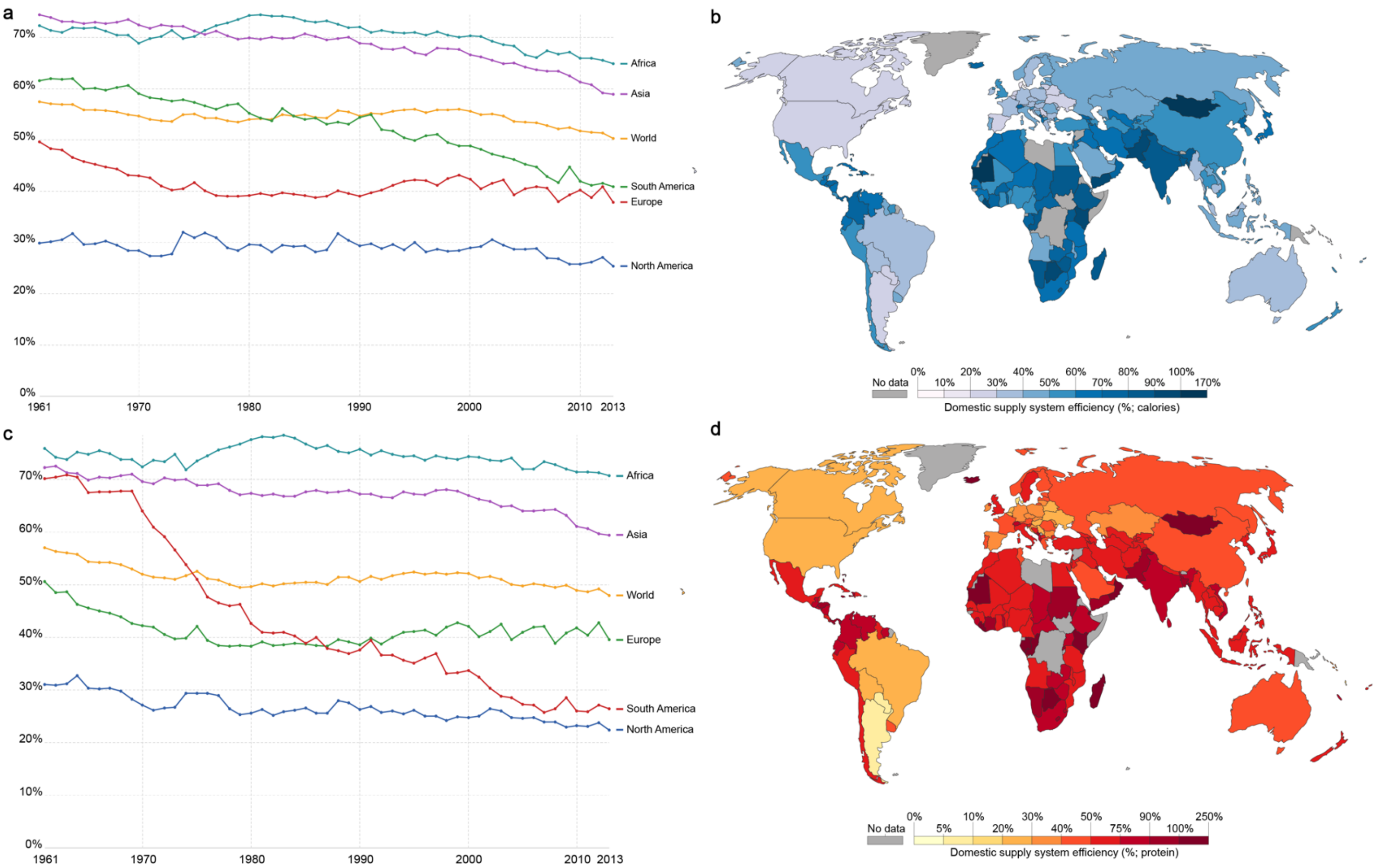

Figure 4a-d: Caloric and protein trade-adjusted (domestic) system efficiencies by region and country (2013). Caloric system efficiency after adjustments for trade (i.e. domestic supply efficiency), (a) by region from 1961 to 2013; and (b) by country in 2013. Domestic protein system (c) by region from 1961 to 2013; and (d) by country in 2013.

While North and South America's efficiencies increased after correction for trade as a result of net exports, the inverse is true of Africa and Asia which were net calorie importers. Being a large net importer, Africa's trade-adjusted efficiency dropped to 65% (down from 79% based on production efficiency). Asia's domestic system efficiency reduced to 59% when adjusted for trade. Its domestic efficiency has shown a marked decline over the last 50 years, falling from a high of 75% in 1961.

Results on trade-adjusted protein system efficiency are shown in Figures 4c-d, detailed in Table 2 and country-level time-series in Supplementary File 1. Even when corrected for trade, protein system efficiency in both North and South America remained low, at 22% and 26% respectively. Europe's domestic supply efficiency—with imports and exports approximately balancing—was similar to its production system efficiency at 39-40% in 2013 (marginally higher than its caloric efficiency at 37%).

Africa's trade-adjusted protein system efficiency was notably higher than its caloric pathway at 71%. Once adjusted for trade, Asia's domestic supply efficiency reduces to 60%, suggesting a large share of its imports were in the form of protein-rich commodities.

Understanding regional and national inefficiencies for optimisation

This analysis attempts to estimate global, regional and national food system efficiencies in calories and protein over the last 50 years. Whilst overall global pathways have been quantified in terms of biomass and calories previously (Bajželj *et al.*, 2014; Alexander *et al.*, 2017), there remains a lack of understanding of the regional differences in system efficiencies, and how these have changed with time.

The choice as to whether to estimate 'food system efficiency' as the ratio between per capita caloric production and final per capita food supply, or domestic calorie supply to final per capita food supply depends on the purpose of the definition of efficiency and the boundaries set. If focused solely on the efficiency by which primary crop production within a given country or region is delivered as final food supply within the same area, the caloric production ratio would be considered the most appropriate metric. In such a case, net exports would be considered a system inefficiency since it reduces the calories available for food supply within a given country.

However, the world's food system is highly globalised, with a total value of 1.4 trillion US dollars in traded food commodities in 2013 (FAO, no date). Current reliance—and growing future dependence—on trade for regional food supply makes global food system interdependencies crucial to ending malnutrition by 2030 (the second Sustainable Development Goal) (FAO, 2017b). Therefore, from a global perspective, caloric exports are not defined as a system inefficiency, making the ratio of domestic supply (including imports, exports and stocks) to final food supply a more appropriate measure of efficiency.

Understanding not only overall food system efficiencies, but also their geographical variations will be key in meeting both food security pressures and environmental goals in the 21st century. Whilst the FAO projects the need for a 60-70% increase in crop calorie production by 2050 to meet the needs of a growing population (Alexandratos and Bruinsma, 2012), our results show that inefficiencies in the global food system exceed 50%. Regionally, such efficiencies are even more extreme, ranging from below 20% in North and South America to 60-80% in Africa and Asia (Figures 2a-d and 4a-d).

Improved understanding of where such inefficiencies exist—and how they may be reduced—could be essential for increasing food availability without the need for additional primary production. The potential sustainability and resource benefits of addressing these inefficiencies could be significant[5,20] and essential if we are to meet international climate, biodiversity and sustainable development targets (Ranganathan *et al.*, 2016; FAO, 2017b).

Understanding the global distribution patterns of calorie and protein production, trade and inefficiencies is also important from the perspective of food security. There were large national and regional inequalities in per capita production across the world, ranging from over 30,000 kcal pppd in Canada (and 1636 g pppd of protein in Argentina), to less than 2500 kcal pppd across several countries in Sub-Saharan Africa (and less than 10 g pppd- of protein in the Arabian Peninsula). In the coming decades, food trade is likely to play an increasingly crucial role in maintaining food security, as well as political stability (Food Security Information Network, 2017), as the compounding impacts of concentrated population and economic growth, and potential resource pressures (including climatic change) will create further disequilibrium between regional food demands and production (Yeung M., Kerr W., Coomber B., Lantz M., 2017). Recognition of where nutritional production is far in excess of domestic demands, and the magnitude of system efficiencies provides an important outlook on where there is potential to bridge future nutritional gaps. Such understanding will be essential if global food security and sustainability goals are to be coupled.

Methods

This analysis has drawn upon UN FAO Food Balance Sheets (FBS), which provide statistics on food commodities across the value chain for all countries and regions since 1961 (FAO, no date). Whilst the FAO acknowledges the imperfection of Food Balance Sheet data, it is to date the most comprehensive—and only—source which allows for such long-term and extensive analysis of the food system across the full value chain.

The FBS report and map the flow of food commodities from production to the food supply level, accounting for diversion to trade, seed, animal feed, other (industrial) uses and supply chain losses (as farm-level, processing and packaging, and distribution losses). These are categoried by specific commodities (e.g. 'wheat and products'; 'rice (milled equivalent)'; 'apples and products'; 'oil, palm') and reported on a mass basis (e.g. thousand tonnes production).

To provide a useful and understandable measure of food supply, these mass quantities can be converted into their macronutrient equivalents (in calories, protein and fat) as per the methodology of the FAO's Food Balance Sheets (FAO, 2001), by multiplying by commodity-specific nutritional composition factors (as shown in Equation 1):

$$Cp_{wheat} = Q_{wheat} * Cd_{wheat} \qquad \text{(Eq.1)}$$

Where Cp_{wheat} is equal to the total caloric output from wheat and its products; Q_{wheat} is total production (p) quantity of wheat commodity in mass quantity; and Cd_{wheat} represents the caloric density (d) of wheat, measured in kilocalories per unit mass. Total protein production by commodity can be calculated similarly by replacing Cd_{wheat} by Pd_{wheat}—the protein density of wheat, measured in grams per unit mass.

To maintain consistency with FAO FBS data, nutritional composition factors as published by the FAO (which represent global average composition factors) were used for this conversion in our analysis (FAO, 2001). Commodity composition factors can vary by production system, geographical region and post-harvest activities (FAO, 2016); therefore, relying on global average composition factors may underestimate or overestimate regional variability to some extent. However, the use of composition factors in line with FAO FBS development is useful in maintaining commodity balances, especially when correcting for international trade using FAO metrics.

Total caloric or protein (P) production at global, regional or national levels (Pc and Pp, respectively) can then be calculated by summing Cp values for all commodities (n) (Equation 2):

$$Pc = \sum Cp_n \qquad \text{(Eq.2)}$$

Calculation of total annual caloric or protein production is limited by its ability to (i) allow for cross-comparisons between countries and regions; and with time due to population changes; (ii) present quantities in an understandable metric in relation to basic individual demand or requirement. We have therefore normalised all metrics to their average per capita per person per day ($pppd^{-1}$) value by dividing total production or supply quantities by the total population of the respective country or region in any given year, and 365 (to convert from annual to daily figures). UN population statistics as found in the FAO database (FAO, no date) (which are used by the FAO to build its balance sheets) were used in these calculations.

In this analysis we utilise three key variables for both calories and protein: primary crop calorie production (Pc); domestic crop calorie availability (Dc) and final food calorie availability (Fc). Primary crop calorie production (Pc) represents the sum of agricultural production of all crop calories in kilocalories $pppd^{-1}$. Domestic crop calorie availability (Dc) is calculated using the same methodology and nutritional composition factors as for Pc, but utilises the FAO's balance sheet metric 'domestic supply quantity'. This metric is calculated as primary production corrected for trade and stock changes (i.e. Pc minus exports, plus imports and changes in stocks) (Equation 3):

$$Dc = Pc - Ec + Ic + \Delta Sc \qquad \text{(Eq.3)}$$

Where Ec is equal to exported calories; Ic equal to imported calories and ΔSc of calories in stock changes.

Final food supply availability (Fc) measures average per capita final food availability, as reported by the FAO's metric 'food supply (kcal/capita/day)' (United Nations, 2015). Note that this figure represents average food *available* for consumption at the consumer level and does not directly represent actual intake (since consumer wastage is not accounted for). Since our analyses are used to attempt to capture overall efficiency of food supply systems, the conversion of crop biomass (i.e. plant-based commodities) into animal products forms an important element. Therefore, whilst Pc and Dc measure only caloric production from crops, Fc is inclusive of both plant and animal-based commodities (therefore capturing the efficiency of this conversion process). Note that this analysis does not capture the efficiency of grazing or non-food crops for animal feed and therefore potentially overestimates the efficiency of this conversion process (since non-food inputs are also required).

Pc, Dc and Fc (and their protein equivalents, Pp, Dp and Fp) are used to define the four key metrics used in this study:

(a) *Caloric (and protein) crop production*: the total primary crop calorie (protein) production globally, regionally and nationally, measured in average per capita terms (kilocalories or grams of protein $pppd^{-1}$);
(b) *Domestic crop caloric and protein supply*: the total domestic crop calorie (protein) supply globally, regionally and nationally after adjusted for trade, measured in average per capita terms (kilocalories or grams of protein $pppd^{-1}$);
(c) *Production system efficiency* which measures the percentage of primary crop food production which is available (or converted via livestock) into final food supply. This is measured as the ratio of Pc to Fc (or Pp to Fp);
(d) *Domestic system efficiency*: which measures the percentage of domestic (trade-adjusted) crop food supply which is available (or converted via livestock) into final food supply. This is measured as the ratio of Dc to Fc (or Dp to Fp).

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Chapter Two:
Beyond calories: a holistic assessment of the global food system

After article: Ritchie, H., Reay, D. S., & Higgins, P. (2018). Beyond calories: a holistic assessment of the global food system. *Frontiers in Sustainable Food Systems*, *2*, 57. As appears in Chapter Two.

Abstract

The global food system is failing to meet nutritional needs, with growing concerns for health related to both under-, over-consumption and severe micronutrient deficiency. The 2nd Sustainable Development Goal (SDG2) targets the end of malnutrition in all forms by 2030. To address this challenge, the focus around food security and malnutrition must be broadened beyond the scope of sufficient caloric intake to take full account of total nutritional supply and requirements. Here, for the first time, we have quantitatively mapped the global food system in terms of macronutrients, essential amino acids, and micronutrients from 'field-to-fork', normalised to an equitable per capita availability metric. This framework allows for the evaluation of the sufficiency of nutrient supply, identifies the key hotspots within the global food supply chain which could be targeted for improved efficiency, and highlights the trade-offs which may arise in delivering a balanced nutritional system.

1. Introduction

1.1 Global Malnutrition Burden

The global food system is currently failing to meet the nutritional needs of a growing human population (FAO et al. 2015),(FAO 2017). The standard measure of poor nutrition—caloric hunger—indicates that 815 million (one-in-nine) people were undernourished in 2014-16 (ibid). The Food and Agricultural Organisation (FAO)'s most recent analysis suggests that under business-as-usual (BAU) progress, by 2030, 653 million people will remain undernourished globally (FAO 2017). These metrics, however, severely underestimate the scale of the challenge in delivering a nutritionally-sufficient diet for everyone (Sukhdev et al. 2016). Malnutrition exists in various forms beyond insufficient energy intake: it's estimated that approximately one billion people suffer from protein deficiency (Wu et al. 2014); one-third of under-5s are born stunted (low height-for-age)(Ahmed et al. 2012); more than two billion suffer from micronutrient deficiencies (MiNDs, also known as 'hidden hunger') (von Grebmer et al. 2014); and paradoxically two billion adults are classified as overweight or obese, with strong links to an alarming rise in the prevalence of non-communicable diseases (NCDs) such as type-II diabetes and heart disease (International Food Policy Research Institute 2016). This challenge exists across countries of all income levels, with a growing number of developing nations experiencing a 'double burden'—an increase in the prevalence of obesity in parts of the population while undernourishment is still widely prevalent (Alexandratos & Bruinsma 2012). The widespread and multifaceted nature of malnutrition not only comes at a severe social cost, but also an economic one. It's estimated that malnutrition could negatively impact global gross domestic product (GDP) by 10% per year (Horton & Steckel 2011).

The Millennium Development Goals (MDGs) largely limited measures of malnutrition to energy undernourishment (United Nations 2001). The Sustainable Development Goals (SDGs) have broadened this perspective to include the ambition to end all forms of malnutrition (SDG2) by 2030 (United Nations 2015a), making this challenge inclusive of all countries at all income levels. Whilst the importance of nutrition is exemplified in the second SDG (SDG2), malnutrition forms a core component of many of the other SDGs, with highly relevant indicators in gender equality, healthy life, poverty, reducing inequality, education, peace and justice, and growth and employment (International Food Policy Research Institute 2016). The co-dependence of agriculture and environment means it is also tightly linked to SD Goals 13-15, concerned with climate change, oceans and terrestrial ecosystems. In particular, global food production must adapt to environmental change, but also play a key role in climate change mitigation (IPCC 2014).

The inadequacy of a caloric-based outlook to, by itself, address these challenges has led to recent calls for a major reframing of our global approach to malnutrition and food research (Haddad et al. 2016; Sukhdev et al. 2016). A few fundamental components emerge as crucial to this shift: the food system must be reviewed with the inclusion of all essential nutritional elements; holistically, across the full agricultural and food value chain to identify entry points for change; and with relevant metrics which can be more widely understood and communicated.

1.2 Research aims

Here, for the first time, we have mapped the global flow of all essential nutritional components—including macronutrients, micronutrients (essential vitamins and minerals), and amino acids—from 'field-to-fork', assuming per capita equity (i.e. utilising an average per capita metric) availability. This was quantified drawing upon the FAO's Food Balance Sheets (FBS) for 2011 (the latest complete dataset available) (FAO n.d.), FAO regional commodity waste estimates (FAO 2011b); and FAO and the United States Department of Agriculture (USDA) nutritional databases (FAO 2001; FAO 2016; USDA 2016) (see Methods).

This analysis serves several purposes. Firstly, by measuring average nutrient intakes relative to recommended nutritional requirements, it reviews the capacity with which the current food system could sufficiently nourish the current global population through equitable distribution. Secondly, it identifies the key system inefficiencies, which can be compared both across stages of the value chain and across nutritional components, to better understand the entry points which can be targeted for improved efficiency. These entry points may differ between macro- and micronutrients, making a holistic analysis crucial to recognising the trade-offs and balance in optimising both. This will allow for further quantification and analysis of the capacity of the food system to meet growing nutritional demands through time, and SDG targets by 2030. Whilst this has been evaluated previously in the form of calories (Bajželj et al. 2014; Cassidy et al. 2013), this discussion must be extended to all nutritional components if SDG2 is to be met.

There are three core components necessary to deliver an effective food system for everyone:

(1) enough food of balanced nutritional quality must be produced and available for consumption at the household level;

(2) a sufficient and balanced range of commodities must be regionally and locally accessible for consumers;

(3) a diverse range of nutritious products must be affordable for consumers at all income levels.

Our analysis primarily focuses on the first of these three components. By normalising to an average per capita metric, such an analysis fails to capture the global inequalities in nutritional availability and intake which exist, and that are reflected in the latter two components. However, the framework utilised in this study holds merit in its replicability: it can be easily scaled for use at a range of levels including regional, national or local contexts. In this case, such analyses can prove effective in assessing the capability of national food systems or trade to meet domestic nutritional requirements.

2. Methods

The global food system was mapped from crop production through to per capita food consumption using FAO Food Balance Sheets (FBS) from its FAOstats databases (FAO n.d.). FBS provide quantitative data (by mass) on production of food items and primary commodities, and their utilisations throughout the food supply chain. Such data are available at national, regional and global levels. To maintain consistency and ensure use of the best-available data throughout the analysis, FAO data have been utilised at all possible stages. Food Balance Sheet data for 2011 have been used, these being from the latest full dataset available.

Food Balance Sheets provide mass quantities across the following stages of the supply chain: crop production, exports, imports, stock variation, re-sown produce, animal feed, other non-food uses, and food delivered to households. Data on all key food items and commodities across all food groups (cereals; roots and tubers; oilseeds and pulses; fruit and vegetables; fish and seafood; and meat and dairy) are included within these balances. In calculation of animal feed production in the form of oilcakes, FAO figures were normalised to primary crop equivalents based on cake-to-crop conversion factors applied by Davis and D'Odorico (Davis & D'Odorico 2015).

FBS do not provide food loss and waste figures by stage in the supply chain. Food loss figures have been calculated based on commodity-specific regional percentages provided in other FAO literature (FAO 2011b). These percentage figures break food losses down across seven commodity groups and five supply chain stages (agricultural production, postharvest handling and storage, processing and packaging, distribution and consumption). The applied percentage values by commodity type and supply chain stage are provided in Supplementary Table 4. The FAO and FBS report final nutritional figures as "food availability"—these figures have not been corrected for consumption wastage, meaning they often overestimate final consumption. In this study we have attempted to correct for consumption-level wastage to provide a more precise indication of food availability—here, we have referred to final food availability as "residual food availability".

In order to calculate the total macronutrient value in each of these stages, mass quantities (for example, tonnes of wheat, rice, pulses) were multiplied by FAO macronutrient (energy content/calories, protein and fat) nutritional factors (for example, 350 kilocalories per 100g) (FAO 2001). This therefore gives the total quantity of kilocalories, grams of protein and fat at each stage of the global supply chain.

Protein quality is a key concern for many developing nations as a result of a predominance of grain-based diets, with grains tending to have poorer digestibility and amino acid (AA) profiles than animal-based products and plant-based legume alternatives (Wu 2016; Swaminathan et al. 2012). Taking full account of protein quality impacts would require quantification based on the FAO's recommended Protein Digestibility Corrected Amino Acid Score (PDCAAS) and, more recently, the Digestible Indispensable Amino Acid (DIAA) score. These scoring systems calculate protein quality based on a food's most limiting AA. Although ideal for the assessment of protein quality in individual food items, and occasionally applied for analysis of simple dietary composition, PDCAAS and DIAA methods present significant challenges when applied to an aggregate of 100+ food items—limiting AA's, for example, can cancel out between different food items (FAO 2011a). To best quantify limitations in protein quality, protein intakes have therefore been corrected for digestibility using FAO digestibility values (World Health Organization 1991), with amino acid profiles analysed separately. The production and distribution of individual indispensable amino acids (FAO 2011a) were quantified using FAO and USDA composition databases (FAO 2016; USDA 2016).

The sufficiency and requirements of AA intake is measured differently to that of macro- and micronutrients. Whilst the latter are measured in terms of total consumption, AAs are quantified relative to grams of protein intake (mg amino acid per gram of total protein) (WHO/FAO/UNU Expert Consultation 2007). An amino acid is considered to be 'limiting' if its relative (mg g $protein^{-1}$) quantity falls below its AA-specific requirement. When this occurs, protein synthesis cannot proceed beyond the rate at which the limiting AA is available (FAO 2011a). In other words, overall protein utilisation (the total quantity of protein used in the body) is only as effective as its limiting AA. Since amino acid limitation is defined based on AA contents per gram of protein, the relative AA values were calculated using the total protein content at each supply chain stage.

In a similar manner to macronutrients, micronutrients were quantified at each stage of the food chain by multiplying mass quantities of specific commodities by their equivalent micronutrient contents from FAO INFOODS (FAO 2016) composition and USDA nutrient databases[33]. It's important to note that our study attempts to quantify the average supply and availability of nutrients through the commodity chain—micronutrients can additionally be lost through processes such as cooking (World Health Organization 2005), impacting on the true level of consumption in individuals. These additional losses are difficult to quantify. As such, we might consider our results to be an upper estimate on micronutrient availability. In this analysis, the key vitamins and minerals necessary for human health were assessed, including calcium, iron, zinc, folate, and vitamins A, B_6, B_{12} and C.

It should be noted that this analysis considers only natural micronutrient sources within the commodity chain. Vitamins and minerals are frequently added to food products at the processing stage (Miller & Welch 2015). This food fortification process is widely implemented across many developed nations, and can be an essential source of key micronutrients. Such practices are, however, largely absent across most developing nations where natural dietary sources of micronutrients are also likely to be lowest.

For consistency, and to provide a better understanding of the food system down to the individual level, all metrics have been normalised to average per person per day (pppd) metric—this was calculated by dividing total nutrient contents by 2011 global population figures from UN population data (United Nations 2015b). This therefore provides an average value, assuming equitable distribution across the population.

In order to assess the capacity of the global food system to deliver sufficient nutrients for all, this average pppd nutrient availability was compared relative to macronutrient, amino acids and micronutrient recommended requirements. We acknowledge that nutritional requirements vary significantly between individuals depending on gender, age, size, and levels of activity—this study is unable to capture such heterogeneity. However, it does provide an important comparison of equitable average availability and average recommended requirement. In this study we have defined caloric requirements by the World Health Organisation's (WHO's) minimum threshold of 2100 kcal pppd (UNHCR/UNICEF/WFP/WHO 2004), 50 g pppd of protein (World Health Organization 1991), and 70 g pppd of fat (FAO/WHO 2008).

Micronutrient and AA Estimated Average Requirement (EAR) values were used to determine recommended dietary requirements. EAR is defined as the median required intake and is based on the assertion that nutrient intake and requirements are independent; the distribution of requirements falls symmetrically around the EAR value; and the distribution of nutrient intakes is much larger than that of requirements(World Health Organization 2005). Micronutrient and AA requirements - in contrast to some dietary needs such as calories, which have larger inter-individual variabilities in requirement - meet these criteria. WHO guidelines (World Health Organization 2005; WHO/FAO/UNU Expert Consultation 2007) and recommended demographic requirements for calculation of global population EARs (for individuals >12 months of age) have been followed using UN age and gender demographic data (United Nations: Department of Social and Economic Affairs 2013). Full data on EARs by age and gender group, and population weightings are provided in Supplementary Tables 1-3. Individuals which fall below EAR values are defined as being at risk of deficiency.

3. Results

3.1 Macronutrients

The three macronutrients pathways (calories, protein and fat) from agricultural production through to food eaten are shown in Figures 1a-c.

Caloric pathways in the food system are the most well-documented to date. Our analysis indicates an average global per capita availability of 2687 kcal pppd in 2011, well above the minimum requirements of 2100 kcal pppd. Our figure is slightly lower than the FAO's reported average caloric supply of 2869 kcal pppd (FAO n.d.), since we have attempted to estimate residual availability after correction for wastage at the consumption level. This is in contrast to FAO figures, which reports food available for consumption, without correction for wastage at the consumer level (FAO 2001). This result—that globally we produce more than enough calories to meet current energy needs if equitably distributed—is already well-established (Bajželj et al. 2014; Cassidy et al. 2013; Foley et al. 2011). Our analysis provides further support for this conclusion. In reality, an estimated two billion overconsume, and close to 800 million are left undernourished (International Food Policy Research Institute 2016).

To adequately account for protein quality factors, measures of amino acid profile and digestibility must be taken into account (WHO/FAO/UNU Expert Consultation 2007; Wu 2016). In this analysis we have therefore corrected total protein intake by multiplying by commodity-specific digestibility factors (World Health Organization 1991) (as described in Methods), and mapped amino acid pathways individually (see Section 2.1). This correction for protein quality is particularly important in the evaluation of protein intakes in developing countries and low-income households where monotonous cereal-based diets are common (Gómez & Ricketts 2013; FAO 2013). Whilst cereal-dominant diets may meet total protein requirements of 50g pppd, protein intake is often of poor quality and insufficient to meet actual nutritional requirements (Bouis et al. 2011).

Results of this analysis suggest that, once corrected for digestibility, average protein availability was 63g pppd. Despite surpassing the 50g pppd minimum requirement, the distribution of intakes around this average value is likely to be larger than that of calories; the unit costs of protein are generally higher than that of carbohydrates or fats, making protein more income-dependent than energy intake (Drewnowski 2010). This is particularly important for many developing nations where consumption of animal-based products and plant-based alternatives such as pulses are often low (Dror & Allen 2011; Varadharajan et al. 2013). Protein quality is an important factor to consider in evaluating whether intake is sufficient. Studies often report that average regional or national intakes meet 50g pppd requirements (Ranganathan et al. 2016), however, for many low- and middle-income countries where dominant protein sources are cereal- or plant-based (predominantly in sub-Saharan Africa and Asia), average intake may fall below this requirement once digestibility has been considered.

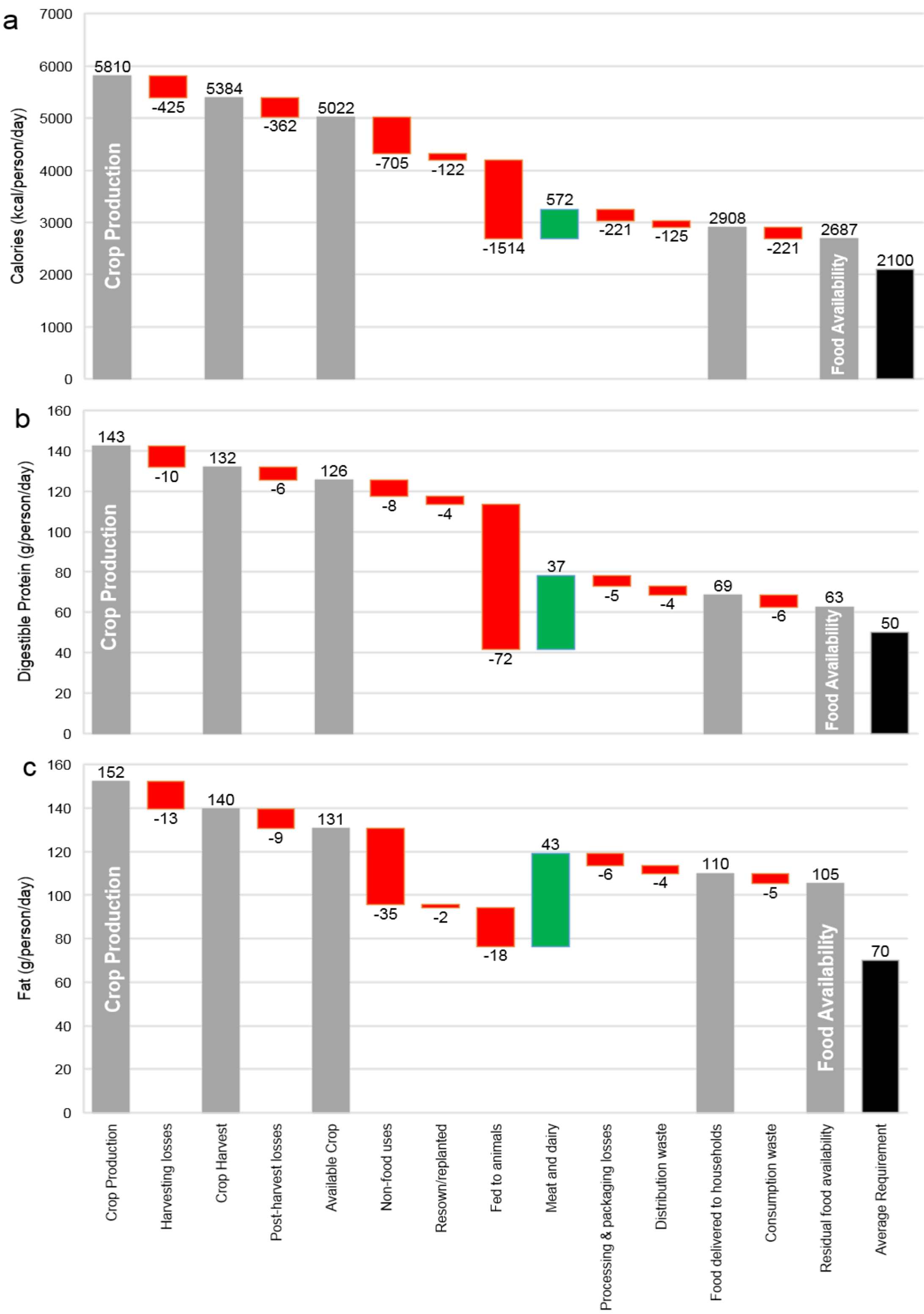

Figure 1: Production and losses in the global food system from 'field to fork' in 2011. Food pathways in (a) calories; (b) digestible protein; and (c) fat from crop production to residual food availability, normalised to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate macronutrient availability at intermediate stages of the chain with the minimum average requirement shown in black.

Our analysis suggests that, with equitable distribution, availability of fat would have been 105g pppd in 2011—well above the required 70g pppd. It is well-established that individual intakes of dietary fat are often in excess of the recommended 70g pppd guidelines, particularly in developed nations (FAO n.d.). This is of concern from a health perspective, with strong links between dietary fat intake, obesity and NCDs such as heart disease and stroke (Bray et al. 2004; Malik et al. 2013). However, it's also important to acknowledge the physiological role of fat in nutritional outcomes, and the negative health impacts which can occur through inadequate consumption. Fat plays an important role in the absorption of key micronutrients (FAO/WHO 2008); low fat intake, as remains the case in many developing nations (FAO n.d.), therefore serves to exacerbate cases of micronutrient deficiency which are prevalent in low-income communities (Jayarajan et al. 1980). The large variations in global intakes of fat therefore have important health implications at both ends of the spectrum.

Whilst the availability of macronutrients at the household level is of prime importance, the average supply of calories, protein and fat are generally well understood (FAO n.d.; FAO et al. 2015). Of greater interest for building future food resilience and more sustainable food systems is to understand the complete food production and use chain in order to identify key inefficiencies and potential intervention points.

The pathways of calories, digestible protein and fat from 'field-to-fork' have both similarities and conflicting patterns, which are important to consider when defining potential entry points for change. All chains experience severe losses across the value chain, with losses of 54%, 56% and 31% in calories, digestible protein and fat respectively. The three macronutrients show similar patterns of loss in stages we would define as supply chain losses (harvesting, post-harvest, processing, distribution, and consumption) with moderate losses at all stages, and the highest in the harvesting phase. As has been previously documented, such patterns will be regionally variable and income-dependent, with major losses at the post-harvest stage in developing nations, and more wastage at the consumer level in higher-income households (Lipinski et al. 2013).

The dominant losses occur in the allocation of edible crops towards non-food uses and animal feed. This is where the pathways between macronutrients differ. The diversion of both calories and fat to non-food uses are much larger than that of digestible protein. The largest commodities utilised for non-food purposes are in the form of oils and cereals. This is an expected result due to large allocation of these commodities for the production of biofuels and industrial products such as cosmetics, construction and polymer materials(Lu et al. 2011; Foley et al. 2011). The re-allocation of oils and cereals explains the comparably larger losses of calories and fat versus digestible protein (which is absent in oil commodities, and of low concentration in cereals) (FAO 2001).

The largest loss of calories and digestible protein occurs in the re-allocation of crops for animal feed. This is in contrast to fat, which generates a net surplus in the production of animal-based fats. Our analysis suggests that approximately 1500 kcal and 70g of digestible protein pppd is diverted for feed. Whilst some energy and protein is converted and re-enters the system in the form of meat and dairy products, both macronutrients experience a significant net loss in this conversion process (Fig. 1a-b). Cereals, roots, and high-quality protein crops such as soybeans form the largest sources of animal feed, which explains the basis of this loss. It is important to note that the complete macronutrient flow in this process is not captured through mapping edible food calories alone; there are also significant energy and protein inputs in the form of grazing, pasture and fodder (land use for animal production is estimated to account for approximately 75% of total agricultural land)(Foley et al. 2011).

3.2 Amino Acids

Digestibility plays a key role in assessing protein quality, however the distribution and intake of essential amino acids (AA) must also be considered. The sufficiency and requirements of AA intake is measured differently to that of macro- and micronutrients. Whilst the latter are measured in terms of total consumption, AAs are quantified relative to grams of protein intake (mg amino acid per gram of total protein) (WHO/FAO/UNU Expert Consultation 2007). An amino acid is considered to be 'limiting' if its relative (mg g protein^{-1}) quantity falls below its AA-specific requirement. When this occurs, protein synthesis cannot proceed beyond the rate at which the limiting AA is available(FAO 2011a). In other words, overall protein utilisation (the total quantity of protein used in the body) is only as effective as its limiting AA.

Our analysis has mapped the relative amino acid contents of all indispensable AAs. At the level of global food consumption, no AAs are deemed to be limiting in the average global diet (Table 1). However, we have highlighted lysine as the amino acid of particular concern (its pathway is shown in Figure 2). As is clearly demonstrable in our analysis, and has been widely discussed within the literature (WHO/FAO/UNU Expert Consultation 2007; Swaminathan et al. 2012), there is a significant contrast in the lysine content of plant- and animal-based products. The lysine content of aggregate commodities towards the top level of the supply chain is distinctly lower than the latter stages, where animal-based products are introduced. Whilst the average diet is not lysine-deficient, if meat and dairy products were removed, the global food system would be severely lysine-limited. At the crop production level, the relative lysine content is 36.6mg g protein^{-1}, much lower than the required value of 46.1 mg g protein^{-1}. The only component of the crop-based system for which the overall lysine content is above this requirement —and only marginally, at 46.9 mg g protein^{-1}—is the portion allocated for animal feed.

	Isoleucine	**Leucine**	**Lysine**	**Methionine +Cysteine**	**Phenylalanine + Tyrosine**	**Threonine**	**Tryptophan**	**Valine**	**Histidine**
Crop Production	35.0	54.9	36.6	26.4	61.4	28.0	9.6	39.1	19.8
Harvesting losses	40.9	66.0	44.4	25.9	62.3	40.6	21.3	0.0	0.0
Crop Harvest	34.6	54.1	36.0	26.5	61.3	27.0	8.7	42.1	21.4
Post-harvest losses	34.5	52.9	32.6	26.0	58.7	24.1	7.9	38.5	19.4
Available Crop	34.6	54.1	36.2	26.5	61.5	27.2	8.7	42.3	21.5
Non-food uses	17.9	36.4	17.8	15.1	37.9	16.7	4.5	24.4	11.8
Resown/replanted	35.7	48.5	39.1	30.7	70.4	30.2	11.2	43.0	21.2
Fed to animals	37.4	64.8	46.9	27.2	63.8	32.3	10.8	43.4	22.7
Meat and dairy	55.4	96.1	103.0	40.5	89.9	49.5	13.8	61.3	36.3
Production and packaging losses	51.8	76.6	56.0	29.0	69.5	34.3	10.8	42.6	24.8
Distribution waste	53.4	85.5	75.2	31.8	77.8	40.8	12.0	50.5	28.9
Food delivered to households	41.5	63.0	56.6	33.4	74.0	32.9	9.2	52.4	28.1
Consumption waste	43.8	61.3	55.0	32.9	72.2	34.0	11.1	44.7	25.4
Residual food availability	**41.3**	**63.1**	**56.8**	**33.4**	**74.2**	**32.7**	**9.0**	**53.1**	**28.4**
Estimated Average Requirement (EAR)	*30.1*	*59.5*	*46.1*	*22.5*	*39.1*	*23.6*	*6.2*	*39.4*	*15.4*

Table 1: Aggregate amino acid profiles by stage in food supply chain. Amino acid (AA) contents (measured per gram of total protein) of aggregated food commodities at each stage of the food production and supply chain. This is measured relative to Estimated Average Requirement (EAR) values. If the AA content falls below EAR values, that AA is considered 'limiting' and can have a negative impact on total protein utilisation.

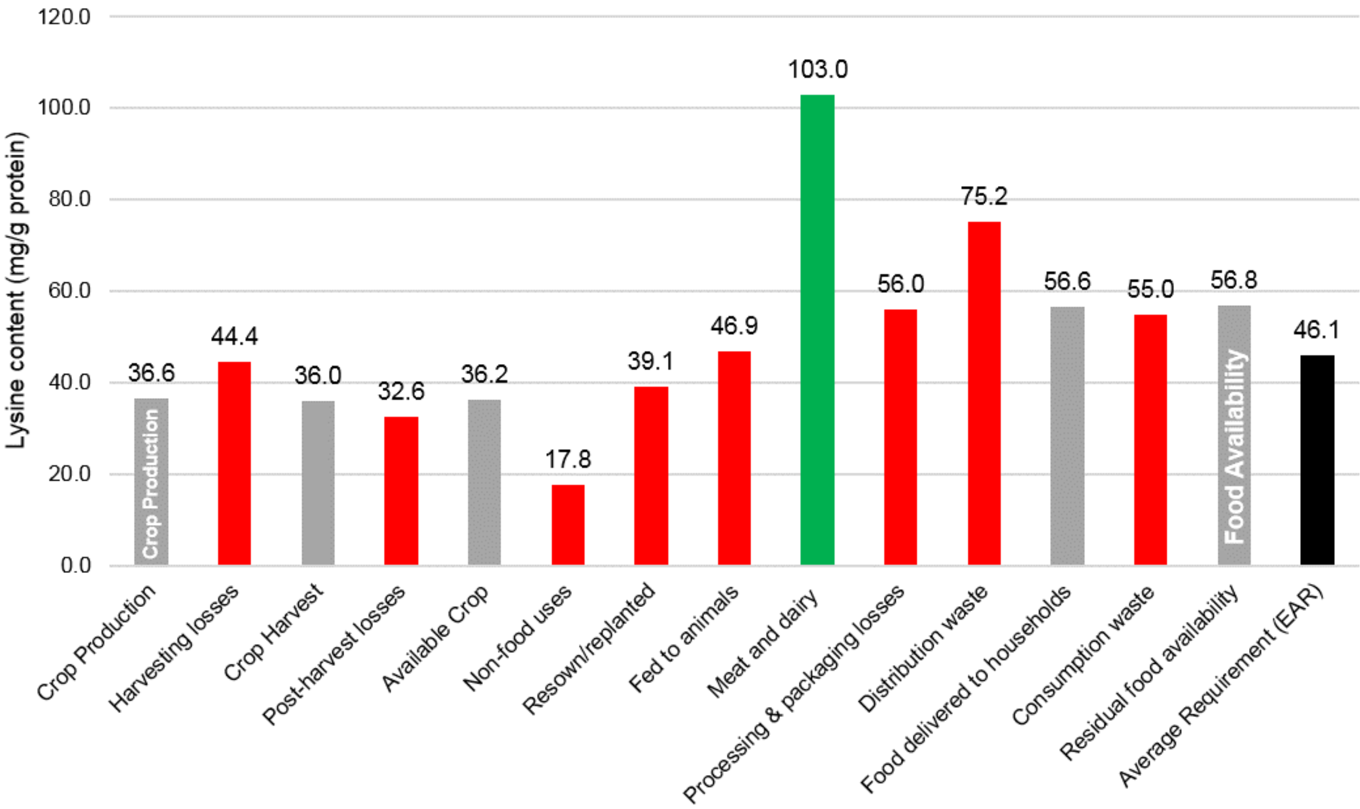

Figure 2: Lysine content of aggregate food commodities at each stage of the global supply chain. Lysine content (measured relative to total protein content as mg gprotein-1) of aggregated food commodities by production and supply chain stage. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; grey bars indicate macronutrient availability at intermediate stages of the chain, with the estimated average requirement shown in black. If the lysine content falls below its EAR value, lysine is considered 'limiting' and can have a negative impact on total protein utilisation.

This finding is important for several reasons. Diets low in intakes of animal-based products—especially those limited for economic reasons (where higher-quality alternatives such as pulses and legumes are not widely consumed) are likely to be lysine-limited. After correction for protein digestibility, this limitation further reduces the level of utilisable protein consumed in low-income settings (WHO/FAO/UNU Expert Consultation 2007).

It also has important implications for the promotion of more sustainable plant-based diets. It's widely acknowledged that the resource footprints of animal-based products are typically higher than crop-based alternatives (Tilman & Clark 2014), driving efforts for the adoption of more plant-based or vegetarian dietary habits (Ranganathan et al. 2016). However, our analysis suggests that our current food system would be severely lysine-limited in the absence of meat and dairy products. Although feed conversion in the production of livestock is inefficient—with large losses of calories and digestible protein—it is essential within our current food system to meet lysine requirements. This does not imply that a global shift towards a plant-based diet could not meet these requirements, however, a major shift in overall agricultural production towards more protein-based crops such as pulses and legumes would be necessary. Since the energy content of these commodities is typically lower than that of staple carbohydrate crops(FAO 2001; USDA 2016), the displacement of agricultural land used for cereal production may result in an overall reduction in total global caloric output. This is an important balance to assess in meeting the caloric, protein and lysine requirements of a growing population. This makes the extension of future analyses beyond caloric production even more essential.

3.3 Micronutrients

In this analysis, we have selected eight micronutrients which are typically analysed in nutritional assessment: calcium, iron, zinc, folate, and vitamins A, B_6, B_{12} and C. In comparison to macronutrients, the concentration of micronutrients can be more challenging to map through the supply chain since non-quantified losses can occur at stages such as storage, transport and in cooking (World Health Organization 2005). Here, we have assumed the commodity-specific concentrations from FAO INFOODS (FAO 2016) and USDA (USDA 2016) databases. We therefore suggest that since losses from stages such as cooking have not been quantified, our estimates may be considered the upper limit of actual micronutrient values.

Estimated Average Requirements (EARs) of individual micronutrients have been assessed based on WHO guidelines (World Health Organization 2005), recommended demographic requirements and weighted for the demographic distribution of the global population (>12 months of age) (United Nations: Department of Social and Economic Affairs 2013). Full data on EARs by age and gender group, and global population weightings are provided in Supplementary Tables 1-3. The EAR is defined as the median required intake; in micronutrient assessments, individuals which fall below this value are deemed to be at risk of deficiency. This means that in order to ensure global requirements are met, all intakes must surpass the EAR (not just the average intake).

The pathways of individual micronutrients are presented in Figures 3a-c, 4a-c and 5a-b. As shown, all micronutrients meet their EAR in the global average availability. However, there are several micronutrients for which this is marginal. For example, the average availability of calcium is 953mg pppd relative to 877 mg pppd requirements. Similarly, the availability of folate is only marginally higher than its EAR (with an intake of 313 µg ppd versus 299µg ppd requirements). This would be sufficient if diets were perfectly equitable, however, large geographical variations in dietary availability—especially in micronutrients which, like digestible protein, are typically more income dependent than calories (Drewnowski 2010)—mean that many will consume well below EARs.

Micronutrient pathways demonstrate a trade-off similar to calorie, protein and lysine balances in relation to livestock production. As shown (Figures 3-5a-c), the largest supply chain losses of several micronutrients (folate, zinc, iron, vitamin A and calcium) occur in the allocation of crops to animal feed. Whilst this highlights an important inefficiency in the food system, this conversion is essential in the production of vitamin B_{12}, for which animal-based products are the only dietary source (Wu et al. 2014). This dependence on meat and dairy products is likely to leave many individuals at risk of deficiency (especially in calcium, iron, zinc, folate vitamin A, C and B-vitamins), especially those in lower income groups.

Our results indicate that the magnitude of total micronutrient loss from 'field-to-fork' is typically higher than that of macronutrients. All micronutrients assessed in this study—with the exception of vitamin B_{12}—experience total losses of over 60%. In the case of folate, this inefficiency reaches 71%. This result is a reflection of the large losses and wastage of highly perishable foods, such as fruits, vegetables and animal-based products (FAO 2011b).

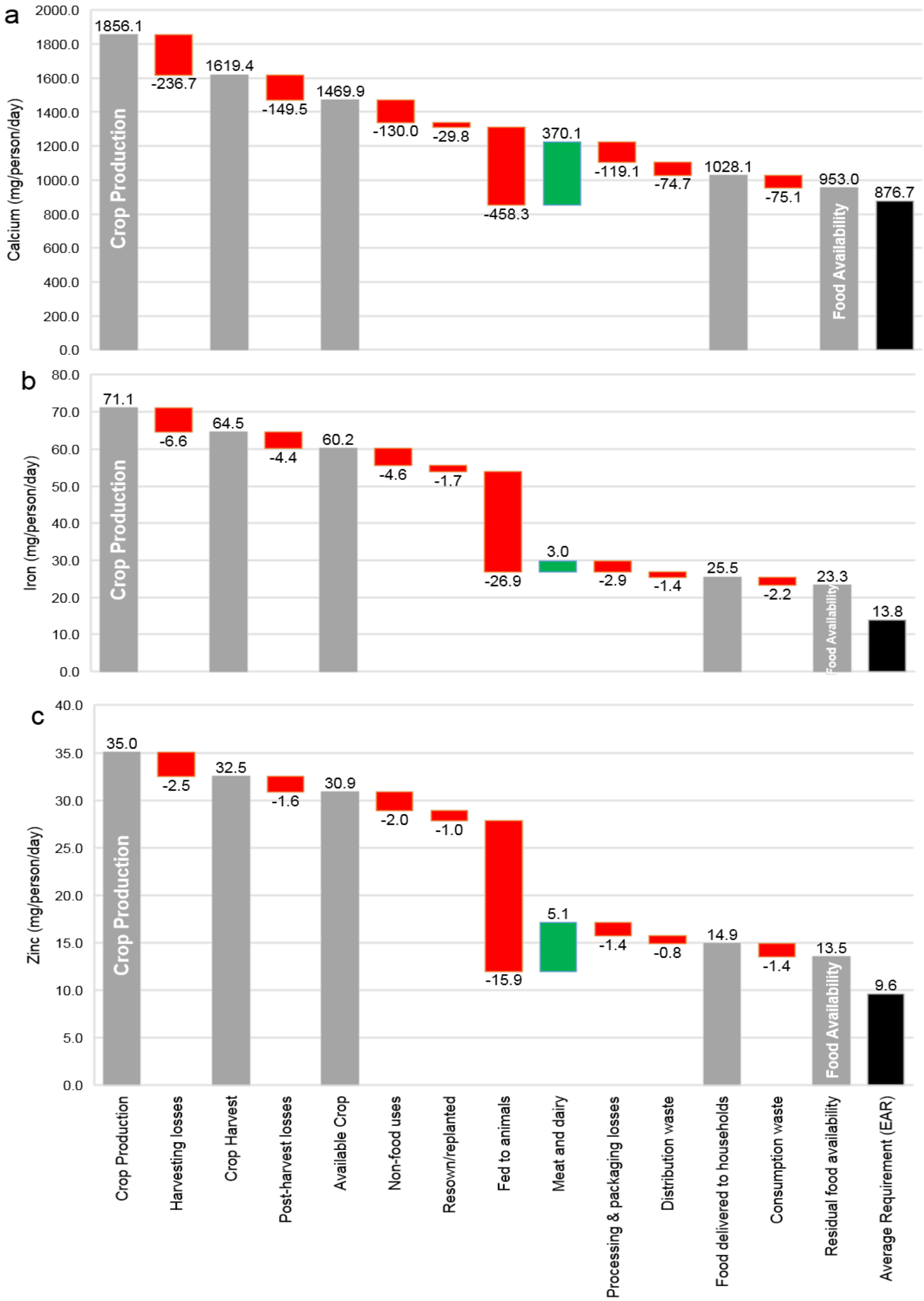

Figure 3: Production and losses of micronutrients in the global food system from 'field to fork' in 2011. Food pathways in (a) calcium; (b) iron; and (c) zinc from crop production to residual food availability, normalised to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; grey bars indicate macronutrient availability at intermediate stages of the chain, with the estimated average requirement shown in black.

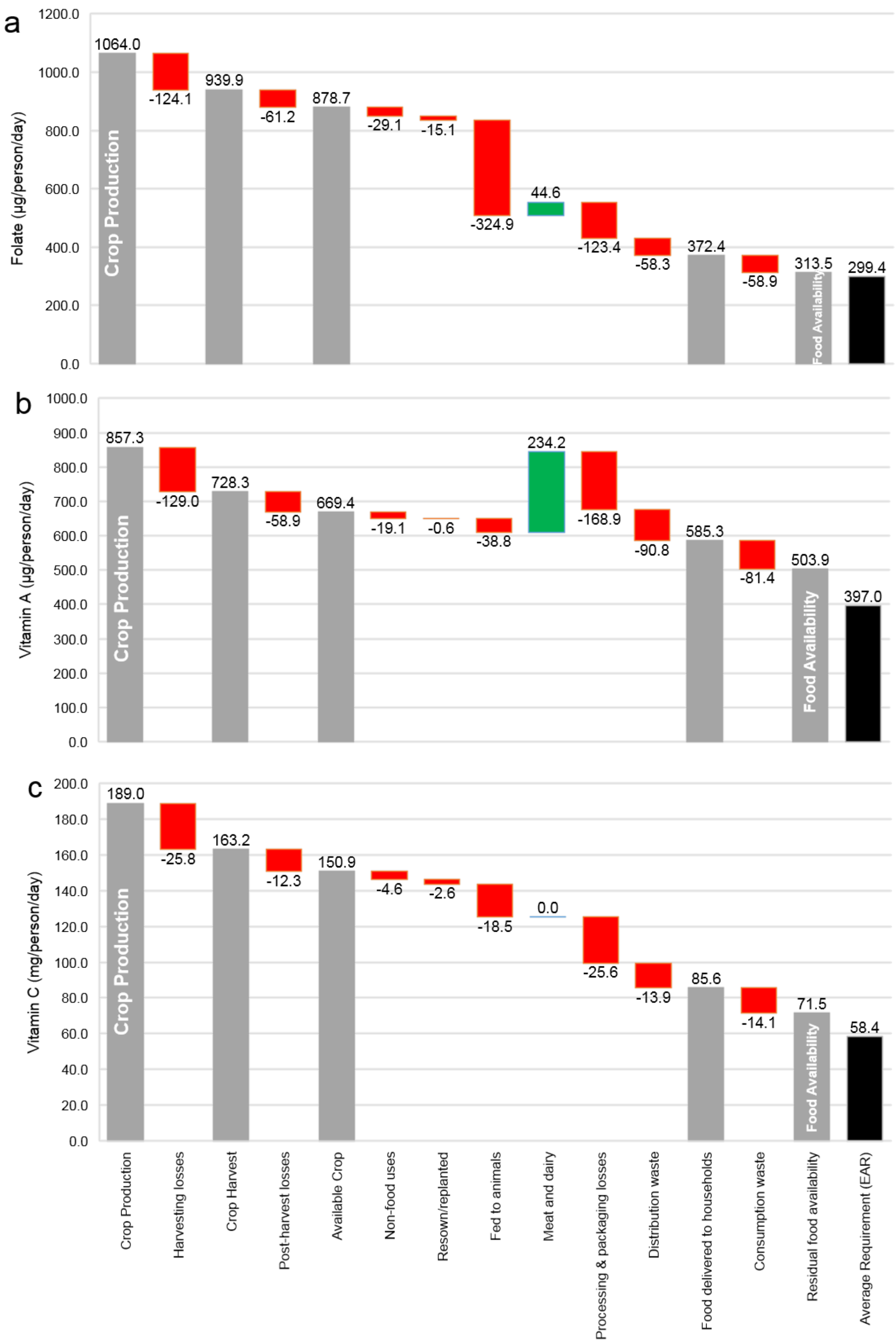

Figure 4: Production and losses of micronutrients in the global food system from 'field to fork' in 2011. Food pathways in (a) folate; (b) vitamin A; and (c) vitamin C from crop production to residual food availability, normalised to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate macronutrient availability at intermediate stages of the chain, with the estimated average requirement shown in black.

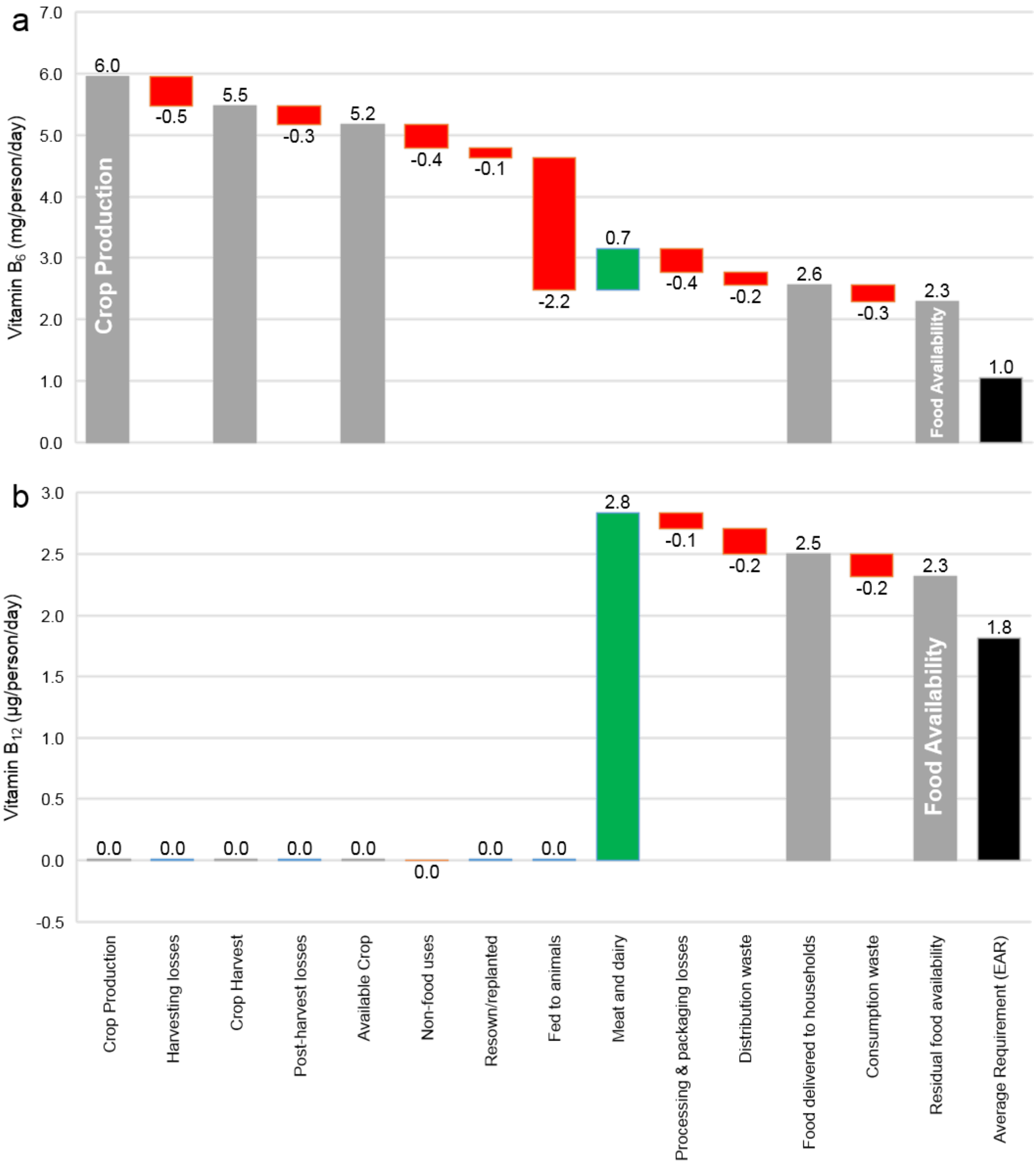

Figure 5: Production and losses of micronutrients in the global food system from 'field to fork' in 2011. Food pathways in (a) vitamin B6; and (b) vitamin B12 from crop production to residual food availability, normalised to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate macronutrient availability at intermediate stages of the chain, with the estimated average requirement shown in black.

4. Discussion

This study has attempted to holistically map the global food commodity and nutrient system from agricultural production through to food eaten—a system which is complex, and in some cases, poorly quantified. To maintain methodological consistency, we have utilised FAO FBS, regional waste and nutritional composition data as far as possible—the FAO is currently the only data repository from which such a global analysis can be sourced. The uncertainty around FBS and waste data is fully acknowledged by the FAO (FAO 2001). As such, we acknowledge that our analysis is not perfect in a statistical sense (see Section 4.1- Data Limitations), however, it is currently the best estimate of the global food nutrient system to date.

Our analysis further highlights the importance of extending food and nutritional analysis beyond the scope of calories—complex trade-offs arise in sufficient production of macronutrients, amino acids and micronutrients. Meeting future food demand (and SDG2 targets) requires a holistic overview of each across the full commodity system. It is from this starting point that the focus and efficacy of interventions can be quantified and balanced to better meet global nutritional demands. The effectiveness of particular interventions is likely to be component-dependent. For example, the disproportionately large losses of many micronutrients across the supply chain mean that strategies which focus on improved storage and distribution management are likely to improve micronutrient availability even more than macronutrient availability. Balancing and optimising these intervention options to meet context-specific deficiencies is vital in reducing the scale of global nutrient deficiency.

Despite providing an important global overview of the overall food system, this analysis has limitations in its effectiveness at capturing regional, national and local system dynamics. That said, this framework is highly replicable—FAO data exist at regional and national levels—and can be scaled for more context-specific nutritional analysis. Such scalability will allow for better coverage of the dietary inequalities which exists both between and within countries.

4.1 Data Limitations

The challenge in developing accurate Food Balance Sheets (FBS) at the national and global level are widely acknowledged and discussed by the FAO (FAO 2001). The accuracy of FBS is constrained by the completeness and reliability of commodity production and utilisation statistics in national records.

Food loss and waste figures, especially in countries where small-holder farms and local markets are prevalent, has a high level of uncertainty. To our knowledge, statistics on supply chain losses and waste down to the national level are not widely available, particularly at the resolution of commodity and chain stage breakdown. For this reason, published commodity-specific FAO figures on regional losses have been applied in this study (Supplementary Table 4). A reliance on aggregated regional values reduces the resolution to which supply chain losses can be quantified, and introduces an additional degree of uncertainty.

Where data within FBS are deemed to be incomplete or inconsistent, the FAO draw upon judgements from national expert opinion and technical expertise to provide as reflective coverage as possible in its FBS. Whilst likely to provide a close approximation, this is rarely 100% accurate.

Nonetheless, the FBS is currently the best available data source for construction and analysis of complete commodity chain analysis. Literature is available based on studies conducted at the household level (Swaminathan et al. 2012), however, very few studies attempt to provide coverage of the food chain dynamics from crop production through to human consumption, especially on a global basis as in the present study. Without a complete overview of the commodity chain, the impacts of interventions (such as improved food management and storage; trade; reduced allocation of crops to non-food uses; improved crop yields) are almost impossible to assess.

As the FAO notes, food balance sheets "provide an approximate picture of the overall food situation in a country and can be useful for economic and nutritional studies, for preparing development plans and for formulating related projects" (FAO 2001). In this study, we have therefore relied on FAO datasets in order to construct a high-level overview of the global commodity chain to assess its overall capacity to meet nutritional demands at present. This overview will not be perfect in a statistical sense, however these issues are global in scale and hence we deem the analysis to be appropriate to inform broad policy focus and assess the potential of supply chain interventions.

Improved agricultural, food waste and nutritional reporting would allow for more robust estimates to be constructed. Such data collection will be important in informing future policy and allowing for forward planning in this sector. It should therefore be an area of renewed focus for global food and nutritional assessment in the coming years.

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Chapter Three:

Sustainable Food Security in India – Domestic Production and Macronutrient Availability

After article: Ritchie, H., Reay, D., & Higgins, P. (2018). Sustainable food security in India—Domestic production and macronutrient availability. *PLoS One*, 13(3), e0193766.

Abstract

India has been perceived as a development enigma: recent rates of economic growth have not been matched by similar rates in health and nutritional improvements. To meet the second Sustainable Development Goal (SDG2) of achieving zero hunger by 2030, India faces a substantial challenge in meeting basic nutritional needs in addition to addressing population, environmental and dietary pressures. Here we have mapped - for the first time - the Indian food system from crop production to household-level availability across three key macronutrients categories of 'calories', 'digestible protein' and 'fat'. To better understand the potential of reduced food chain losses and improved crop yields to close future food deficits, scenario analysis was conducted to 2030 and 2050. Under India's current self-sufficiency model, our analysis indicates severe shortfalls in availability of all macronutrients across a large proportion (>60%) of the Indian population. The extent of projected shortfalls continues to grow such that, even in ambitious waste reduction and yield scenarios, enhanced domestic production alone will be inadequate in closing the nutrition supply gap. We suggest that to meet SDG2 India will need to take a combined approach of optimising domestic production and increasing its participation in global trade.

1. Introduction

In 2015, the United Nations (UN) committed to achieving zero hunger by 2030 as the second of the Sustainable Development Goals (SDGs). An important element of this goal is to end all forms of malnutrition, including agreed targets on childhood stunting and wasting. This represents an important progression beyond the Millennium Development Goals (MDGs), where food security was defined and measured solely on the basis of basic energy requirements (caloric intake), and prevalence of underweight children (United Nations, 2001). This new commitment has significant implications for the focus of research and policy decisions; it requires a broadening of scope beyond the traditional analysis of energy intake, and inclusion of all nutrients necessary for adequate nourishment.

India offers a potentially unique example in the development of models and mechanisms by which nutritional needs can be addressed sustainably. In 2016, India ranked 97 out of 118 on the Global Hunger Index (GHI)—this rates nations' nutritional status based on indicators of undernourishment, child wasting, stunting and mortality (Klaus von Grebmer, Jill Bernstein, Nilam Prasai, Shazia Amin, 2016). Despite ranking above some of the world's poorest nations, India's reduction in malnourishment has been slow relative to its recent strong economic growth and puts it behind poorer neighbouring countries (Banerjee, 2014); India has fallen from 80th to 97th since 2000.

India's nutritional problems are extensive. In 2016, 38.7% of children under five were defined as 'stunted' (of below average height) (Klaus von Grebmer, Jill Bernstein, Nilam Prasai, Shazia Amin, 2016), a strong indicator of chronic malnourishment in children and pregnant women, and a largely irreversible condition leading to reduced physical and mental development (Jeyaseelan, Jeyaseelan and Yadav, 2016). Malnourishment within the adult population is also severe, with approximately 15% of the total population defined as malnourished. The issue of malnutrition in India is complex, and determined by a combination of dietary intake and diversity, disease burden (intensified by poor sanitation and hygiene standards), and female empowerment and education (Bhutta, 2016). Improvements in dietary intake alone will therefore by insufficient to eliminate malnutrition, however it forms an integral component alongside progress in other social and health indicators—particularly sanitation. Quantification of India's micronutrient and amino acid profiles, and recommendations for addressing these deficiencies have been completed as a follow-up paper (Ritchie et al. in submission) to provide a more holistic overview of its nutritional position.

India’s nutritional and health challenges are likely to be compounded in the coming decades through population growth and resource pressures. Its current population of 1.26 billion is projected to increase to 1.6 billion by 2050, overtaking China as the world’s most populous nation (United Nations, 2015). India has also been highlighted as one of the most risk-prone nations for climate change impacts, water scarcity, and declining soil fertility through land degradation (Roberts, 2001).

A number of studies have focused specifically on Indian food intake and malnutrition issues from survey assessments at the household level (Varadharajan, Thomas and Kurpad, 2013). The emphasis within India’s agricultural policy and assessment of its success has traditionally been on energy (caloric) intake (Kadiyala *et al.*, 2014). Since the Green Revolution in the 1970s, agricultural policies have been oriented towards a rapid increase in the production of high-yielding cereal crops with a focus to meet the basic calorific needs of a growing population. India has attempted to reach self-sufficiency predominantly through political and investment orientation towards wheat and rice varieties (Laxmaiah *et al.*, 2013). While production of staple crops has increased significantly, India’s agricultural policy focus on cereal production raises a key challenge in simultaneously meeting nutritional needs in caloric, high-quality protein and fat intakes. Few studies have addressed the system-wide balance between supply and demand of the three key macronutrients - calories, protein and fat; nor have they assessed the importance of protein quality through digestibility and amino acid scoring. This assessment is particularly significant for India as a result of its extensive and complex malnutrition issues. Whether India is capable of meeting these macronutrient needs in the future through domestic production improvements alone is of prime importance for study, as a result of its growing population and policy orientation towards self-sufficiency.

Improving the availability and access to food at the consumer level requires an understanding of how food is created and lost through its various pathways across the full agricultural supply chain. Here, for the first time, we have attempted to capture this high-level outlook from crop harvesting to residual food availability across the three macronutrient categories.

2. Methods

2.1 Mapping the current Indian food system

The Indian food system was mapped from crop production through to per capita food supply using FAO Food Balance Sheets (FBS) from its FAOstats databases (FAO, 2001). FBS provide quantitative data (by mass) on production of food items and primary commodities, and their utilisations throughout the food supply chain. Such data are available at national, regional and global levels. Food Balance Sheet data for 2011 have been used, these being from the latest full dataset available.

Food Balance Sheets provide mass quantities across the following stages of the supply chain: crop production, exports, imports, stock variation, re-sown produce, animal feed, other non-food uses, and food supplied (as kg per capita per year). Data on all key food items and commodities across all food groups (cereals; roots and tubers; oilseeds and pulses; fruit and vegetables; fish and seafood; and meat and dairy) are included within these balances.

While there are uncertainties in FAO data (see Supplementary Information for further discussion on FAO data limitations), FBS provide the only complete dataset available for full commodity chain analysis. Therefore, while not perfect, they provide an invaluable high-level outlook of relative contribution of each stage in the food production and distribution system. As shown in this study (see Results section below), a top-down model using FAO FBS has a discrepancy of <10% with national nutrition survey results at the household level.

FBS do not provide food loss and waste figures by stage in the supply chain. To maintain consistency with FAO literature, food loss figures have therefore been calculated based on South Asian regional percentages within FAO publications (FAO, 2011b). These percentage figures break food losses down across seven commodity groups and five supply chain stages (agricultural production, postharvest handling and storage, processing and packaging, distribution and consumption). The applied percentage values by commodity type and supply chain stage are provided in Supplementary Table 1.

In order to calculate the total nutritional value at each supply chain stage, commodity mass quantities were multiplied by FAO macronutrient nutritional factors (FAO, 2001). In this analysis, energy content (kilocalories), protein, and fat supply were analysed. Protein quality is a key concern for India in particular as a result of its largely grain-based diet, with grains tending to have poorer digestibility and amino acid (AA) profiles than animal-based products and plant-based legume alternatives (Swaminathan, Vaz and Kurpad, 2012). To best quantify limitations in protein quality in the Indian diet, protein intakes have therefore been corrected for digestibility using FAO digestibility values (World Health Organization, 1991).

For consistency, and to provide a better understanding of the food system down to the individual supply level, all metrics have been normalised to average per person per day (pppd) availability using UN population figures and prospects data (United Nations, 2015). Whilst this provides an average per capita availability value, it does not account for variability in actual macronutrient supply within the population. To help adjust for this, we have also estimated the assumed distribution of supply of each macronutrient using the FAO's preferred log-normal distribution and India-specific coefficient variation (CV) factor of 0.26 (FAO, 2014). Whilst we recognise that food requirements vary between demographics based on age, gender and activity levels, the normalisation of food units to average per capita supply levels is essential in providing relatable measures of food losses within the system, and its measure relative to demographically-weighted average nutritional requirements (as described below) is appropriate in providing an estimation of the risk of malnourishment.

Estimated macronutrient supply has then been compared to recommended/minimum intake values. The FAO defines the "Average Daily Energy Requirement" (ADER)—for India's demographic specifically—as 2269kcal pppd; ADER is defined as the average caloric intake necessary to maintain a healthy weight based on the demographics, occupation, and activity levels of the population (FAO, IFAD and WFP., 2015). Minimum daily intake of high-quality protein is typically defined for an average individual to be 50g (FAO, 2011a). Dietary fat intake plays a key dietary role in the absorption of essential micronutrients. Several vital vitamins, including vitamin A, D, E and K are fat-soluble—insufficient intake can therefore result in poor micronutrient absorption and utilisation (Reboul, 2013). Inadequate fat intake can therefore exacerbate the widespread 'hidden hunger' (micronutrient deficiency) challenge in India (Vijayaraghavan, 2002) through poor nutrient absorption. However, daily requirements for fatty acids are less straightforward to determine, relative to energy or protein—there is no widely-agreed figure for total fat requirements for adequate nutrition (FAO/WHO, 2008). The resolution of food balance sheet data does not allow us to adequately quantity the availability to the level of specific fatty acids. As a result, although we have mapped pathways of total fat availability through the food system in a similar manner to energy and protein, we have not here attempted to quantity the prevalence of potential insufficiency at the household level.

2.2 Mapping potential near-term and long-term scenarios

Our initial analysis identified two mechanisms potentially crucial in increasing food availability at the household level: reduction of harvesting, postharvest and distribution losses; and improvements in crop yields. Medium-term (through to 2030) and long-term (2050) scenarios have therefore been mapped based on use of these mechanisms. It should be noted that these scenarios are focused on domestic **supply-side** measures to enhance food availability as opposed to demand drivers related to consumer preferences.

A 2030 baseline scenario (assuming yields stagnate and population growth continues in line with UN projections) and three alternative scenarios to 2030 were analysed:

Scenario 1 (halving food supply chain losses): it was assumed that a significant shift in post-harvest management practices, appropriate refrigeration, and efficient distribution allowed for a halving of food loss percentages at the production, postharvest, processing and distribution stages of the supply chain. This would make its relative losses more in line with those of more developed nations (FAO, 2011b). In this scenario consumption (household) waste was assumed to remain constant.

Scenario 2 (achieving 50% AY across all key crops): the halving of food chain losses in scenario 1 was assumed. In addition, it was assumed that all key crops managed to achieve 50% AY through better agricultural management, irrigation and fertiliser practices.

Scenario 3 (achieving 75% AY across all key crops): assumptions as in scenario 2 except an attainment of 75%, rather than 50% AY, has been assumed through crop yield improvements.

Long-term (through to 2050) scenarios were as follows:

Scenario 1 (halving food supply chain losses): the same assumption of halving food loss percentages at the production, postharvest, processing and distribution stages of the supply chain was applied in this scenario. This will require a significant shift in post-harvest management practices, appropriate refrigeration, and efficient distribution, hence 50% reduction represents a magnitude which is more likely to be achieved in this long-term scenario than in the near-term.

Scenario 2 (achieving 75% AY across all key crops): the same assumption of a closure of the yield gap to 75% AY across all crop types, as in the near-term scenario 3, was applied.

Scenario 3 (achieving 90% AY across all key crops): it was assumed that all crop types managed to achieve closure of the yield gap to 90% AY.

To correct for 2030 and 2050 population estimates, all metrics were re-normalised to 'per person per day' (pppd) based on a projected Indian population estimate from UN prospects medium fertility scenarios(United Nations, 2015).

To best demonstrate the food production potential of current agricultural support mechanisms, such as governmental policy and subsidy (which largely determine crop choices), the relative allocation of crop production was assumed constant. It was also assumed that production increases were achieved through agricultural intensification alone; this assumption was based on FAOstats data which has shown no increase in agricultural land area over the past decade, indicating a stagnation in agricultural extensification (http://faostat.fao.org/beta/en/#home).

Crop yield increases were derived based on closure of current farm yields (FY) to reported attainable yields (AY). FY is defined as the average on-farm yield achieved by farmers within a given region, and AY is defined as the economically attainable (optimal) yield which could be achieved if best practices in water and pest management, fertiliser application and technologies are utilised in non-nutrient limiting conditions). Estimates of crop yield improvements were based on given percentage realisations of maximum attainable yields (AY) attained from published Indian crop-specific figures (Mueller *et al.*, 2012). These data are available across all key crop types. Baseline and AY values are provided in Supplementary Table 2.

Significant improvements in yield would predominantly be achieved through improved nutrient and water management. In the present study, scenarios were mapped based on achievement of 50% and 75% AY in the near-term. Fifty percent AY should be technically feasible by 2030: many crops have already reached these values, and those which have yet to do so, typically fall short by 3-5% (see S2 Table for baseline, and AY values). Attainment of 75% AY would be highly ambitious in the near-term, representing an increase of >20% in yield. However, 75% AY and higher may be feasible in the long-term if significant investment in agricultural management and best practice were to be realised in this sector.

Our scenarios to 2050 are therefore modelled on the basis of closure of the yield gap to 75% and 90% AY. To assess whether these estimates were realistic, necessary growth rates were cross-checked based on historical yield growth rates in India. Discussion on this comparison and the suitability of attainable yield valuables utilised in this study are available in the Supplementary Discussion.

Climate change impacts on crop yields remain highly uncertain; the importance of temperature thresholds in overall crop tolerance makes yield impacts highly dependent on GHG emission scenarios. This makes it challenging to accurately quantify 2050 climate impacts. As such, we applied average percentage changes in yields of Indian staple crops based on literature review (Mall *et al.*, 2006) of field-based observations and climate model results. The studies utilised presented results for a doubling of atmospheric CO_2 from pre-industrial levels. This approximates to a business-as-usual (BAU) scenario for 2050(IPCC, 2014). The yield-climate factors applied in this analysis are provided in Supplementary Table 3.

It is projected that, through economic growth and shifts in dietary preferences, meat and dairy demand in India will continue to increase through to 2050. It has been assumed that per capita demand in 2050 is in line with FAO projections; this represents an increase in meat from 3.1kg per person per year (2007) to 18.3kg in 2050, and an increase in milk and dairy from 67kg to 110kg per person per year (Alexandratos and Bruinsma, 2012). We here assume that this increase in livestock production has been met through increased production of crop-based animal feed rather than pasture. The change in macronutrient demand for animal feed was calculated based on energy and protein conversion efficiency factors for dominant livestock types (beef cattle, dairy cattle, ruminants and poultry) (Herrero *et al.*, 2013).

Our analysis assumes that the per person allocation of crops for resowing and non-food uses, and the relative allocation of land for respective crop selection, is the same as in the initial baseline (2011) analysis.

3. Results

3.1 Current food system pathways

The pathways of macronutrients from crop production to residual food availability are shown for calories, digestible protein and fat in Figs 1a-c. Across all macronutrients, the relative magnitude of exports, imports and stock variation is small, and approximately balance as inputs and outputs to the food system. This result is in line with India's orientation towards meeting food demand through self-sufficiency agricultural policies (Subramaniam and Subramaniam, 2009; Swaminathan and Bhavania, 2013). This study's scenarios are therefore designed to assess whether this same emphasis on self-sufficiency in food supply through to 2050 could be achieved through waste reduction and crop yield improvements alone.

In 2011, India produced 3159kcal, 72g of digestible protein, and 86g of fat per person per day (pppd) (Figure 1a-c). Across the system, this resulted in average food availability of 2039kcal, 48g digestible protein, and 49g fat pppd; this represents a loss across the food supply system of 35%, 33%, and 43% in calories, digestible protein, and fat respectively.

Our top-down supply model has been cross-checked against India's National Sample Survey (NSS) data—this reports nutritional intakes bi-annually measured through national household surveys. In its 68th Round (2011-12) report, the NSS reported average daily intakes of 2206kcal and 2233kcal in urban and rural areas, respectively; 60g of protein in both demographics; and 58g (urban) and 46g (rural) of fat (National Sample Survey Office, 2014). Our top-down analysis therefore suggests slightly lower caloric availability than NSS intake figures (but with a discrepancy of <10%); and strong correlation regarding fat intake. Since NSS data reports total protein and take no account of quality or digestibility, our results of digestible protein are not directly comparable. However, with digestibility scores removed, our analysis suggests a total average protein availability of 57g pppd — within 5% of NSS intake results.

Despite the acknowledged uncertainties in FAO FBS datasets (see Supplementary discussion), the strong correlation (within 5-10%) between our top-down supply model and reported household intakes (bottom-up approach) gives confidence in the use of FBS data for high-level food chain analyses such as attempted here.

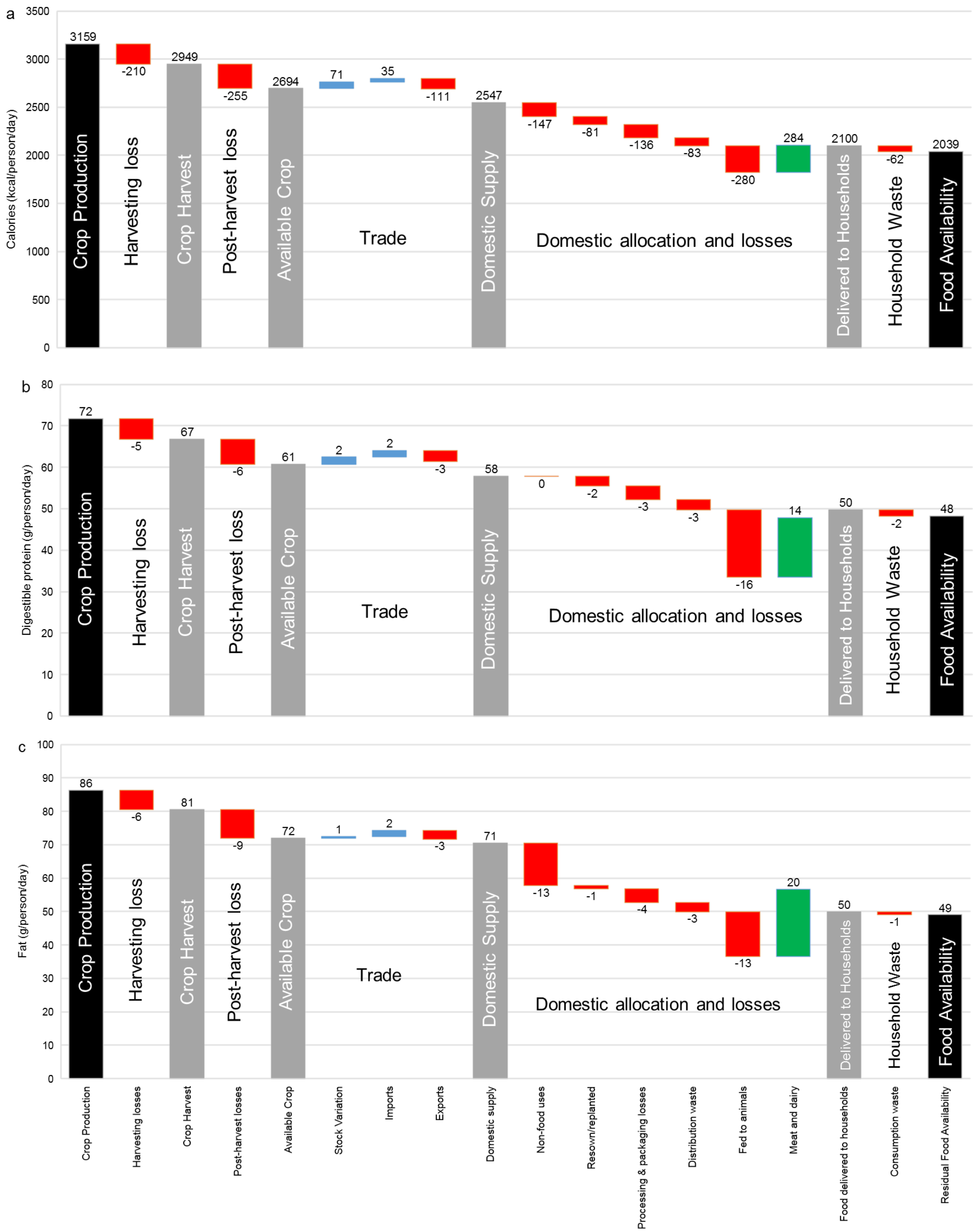

Figure 1: Production and losses in the Indian food system from 'field to fork' in 2011. Food pathways in (a) calories; (b) digestible protein; and (c) fat from crop production to residual food availability, normalised to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate macronutrient availability at intermediate stages of the chain.

The largest sources of loss identified in the Indian food system for calories and protein lie in the agricultural production and post-harvest waste stages of the chain, with lower but significant losses in processing and distribution. Consumption-phase losses are comparatively small. Higher losses of fat occur predominantly due to the allocation of oilseed crops for non-food uses; this is in contrast to digestible protein where losses to competing non-food uses are negligible.

In contrast to the average global food supply system, the conversion of crop-based animal feed to meat and dairy produce in India appears comparatively efficient, with an input-output ratio close to one for calories and protein, and an apparent small production of fats (Dikshit and Birthal, 2010). It is one of the few agricultural systems in the world where the majority of livestock feed demand is met through crop residues, byproducts and pasture lands—its lactovegetarian preferences tend to favour pasture-fed dairy cattle over grain-fed livestock such as poultry (ibid).

Average per capita supply across all macronutrients falls below average per capita minimum requirements. The magnitude of this issue in India emerges via the population-intake distributions. With extension of average macronutrient availability to availability across the population distribution (using a log-normal distribution with CV of 0.26), 66% (826 million) and 56% (703 million) of the population are at risk of falling below recommended energy and protein requirements, respectively.

3.2 Potential future pathways

3.2.1 Scenario results for 2030

Results from scenario analyses for potential food waste reduction and crop yield improvements are summarised in Table 1. Note that we have assumed no change in income/dietary inequalities, hence the CV in distribution has remained constant.

Scenario	Mean caloric intake; kcal pppd (percentage of population below average requirement)	Mean digestible protein intake; gpppd (percentage of population below average requirement)	Mean fat intake; gpppd
Recommended Daily Intake (RDA)	2269	50	70
2011 Baseline Scenario	2039 (66%)	48 (56%)	49
2030 Baseline Scenario	1665 (89%)	39 (83%)	40
Scenario 1	1754 (84%)	42 (75%)	43
Scenario 2	1675 (88%)	40 (81%)	41
Scenario 3	1831 (80%)	42 (75%)	46

Table 1: Mean macronutrient availability in baseline and potential waste and yield scenarios in 2030. Average macronutrient availability in baseline and projected scenarios to 2030, relative to average population requirements. The percentage of the population which would fall below average requirements based on dietary distribution data is reported in brackets.

Under all scenarios, waste or yield improvements fail to keep pace with population growth through to 2030; average per capita caloric, digestible protein and fat availability all fall below the 2011 baseline. Under current levels of dietary inequality, distribution of availability highlights even greater potential malnourishment. The majority (>75%) of the population are at risk of falling below requirements in energy and protein availability in all scenarios. This represents severe malnutrition across India in 2030, even in the case of significant and ambitious yield and efficiency improvements.

Under these scenarios, India would fall far short of reaching the SDG2 target of Zero Hunger by 2030.

3.2.2 Scenario results for 2050

India's anticipated population growth, in addition to potential impacts of climate change on crop yields, could have severe implications on household macronutrient supply by 2050. Our 2050 baseline scenario demonstrates these potential impacts, assuming gains in crop yields were to stagnate at current levels. The full supply chain pathways are shown in Figure 2a-c. Even at the top level of the supply chain (crop production phase) mean provision per person would fall below average requirements in all macronutrients (2198kcal, 49g protein, and 60g fat per person). Although reducing food system losses plays an important role in improving availability at the household level, this result highlights the necessity of also achieving substantial crop yield improvements at the top of the supply chain.

How these variables impact on availability at the household level in our 2050 baseline, and three scenarios is detailed in Table 2, with baseline distributions provided in Supplementary Figure 1a-c. As shown, even in the case of scenario 1 (halving of supply chain loss and waste), and scenario 2 (increase to 75% of AY), in 2050 greater than 80% of the population would potentially fall below average requirements in energy and protein. Only in the case of significant yield increases to 90% AY (scenario 3) would projected levels of malnourishment approach current levels. This would still leave 62% and 56% of the population at risk of falling below recommended caloric and protein requirements, respectively.

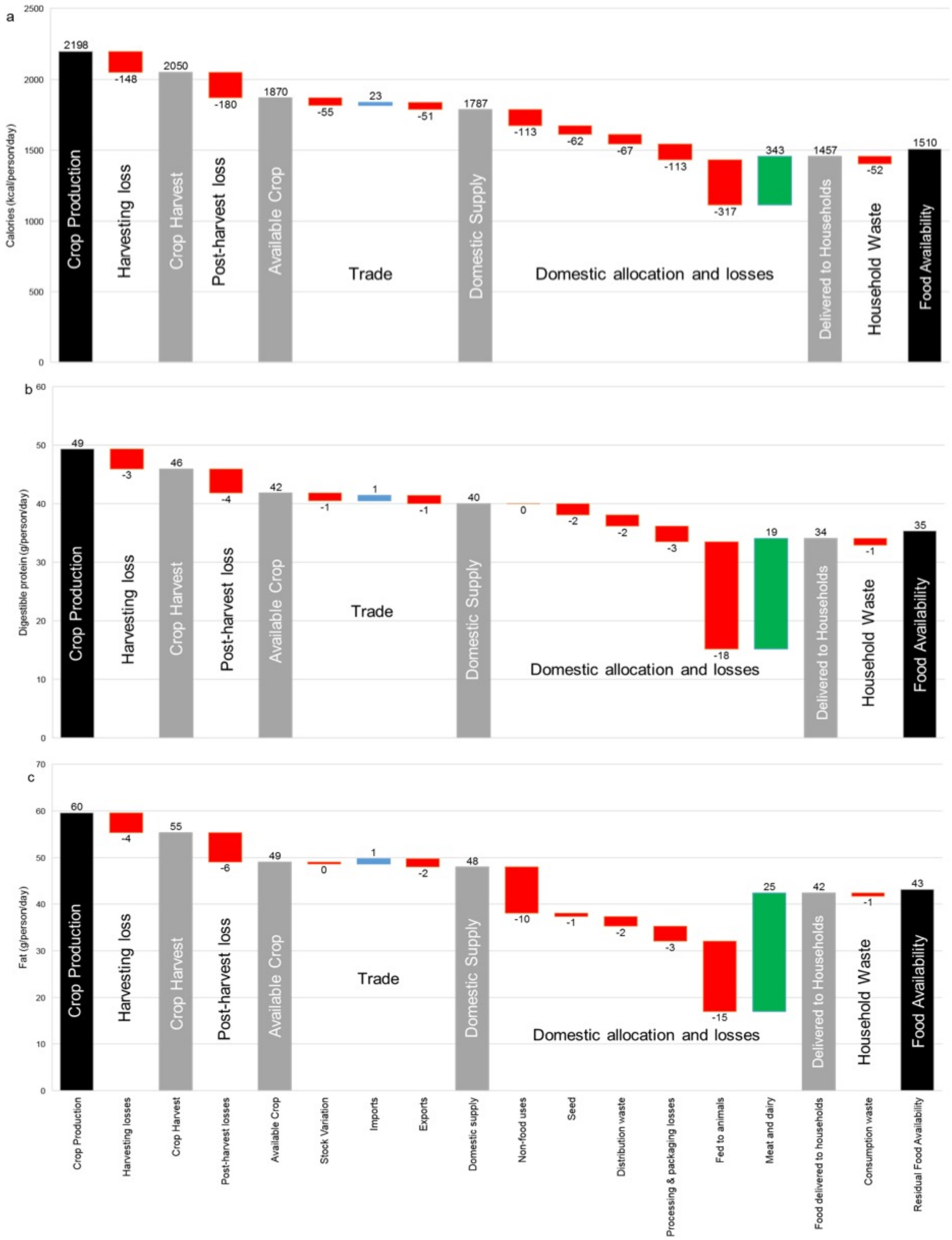

Figure 2: Production and losses in the Indian food system from field to fork under baseline conditions in 2050. Food pathways in (a) calories; (b) digestible protein; and (c) fat from crop production to residual food availability, normalised to average per capita levels assuming equal distribution under 2050 baseline conditions. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate macronutrient availability at intermediate stages of the chain.

Scenario	Mean caloric intake; kcalpppd (percentage of population below average requirement)	Mean digestible protein intake; gpppd (percentage of population below average requirement)	Mean fat intake; gpppd
Recommended Daily Intake (RDA)	2269	50	70
Baseline 2050	1405 (97%)	33 (95%)	42
Scenario 1 (2050)	1661 (89%)	39 (83%)	51
Scenario 2 (2050)	1721 (86%)	40 (81%)	57
Scenario 3 (2050)	2099 (62%)	48 (56%)	66

Table 2: Mean macronutrient availability in baseline and potential waste and yield scenarios in 2050. Average macronutrient availability in baseline and projected scenarios to 2050, relative to average population requirements. The percentage of the population which would fall below average requirements based on dietary distribution data is reported in brackets.

4. Discussion

Our analysis utilised a framework for evaluation of the whole food system (from crop production through to residual food availability) by normalising to consistent and relatively simplistic metrics (per person per day). This holistic approach is critical for identifying levers within the food system which can be targeted for improvements in food security and efficiency of supply. The basic framework is replicable and could therefore be adapted for analysis of any dietary component (for example, micronutrients or amino acids- see Ritchie et al., in review) and at a range of scales (global, regional, or national). This allows for similar analyses to be carried out for any nation, potentially allowing for improved understanding of hotspots in the food system and opportunities for improved efficiency. As such, it could then allow national food strategies to focus on components which are likely to maximise improvements.

Overall, our analyses indicate weaknesses in India's current reliance on domestic food production. Further calculation, based on FAO FBS, make this explicit: in 2011 India's population was 17.8% of the global total, yet produced only 10.8%, 9%, and 11.8% of the world's total calories, digestible protein and fat respectively[1]. Even in a highly efficient food system, self-sufficiency is impossible to achieve based on such production levels and the need to provide sufficient nourishment for all. Likewise, even if Indian population figures were to plateau, it is unlikely that domestic production alone would be sufficient to close the current food gap.

Current malnutrition levels —defined here as insufficient macronutrient availability—in India are already high. Sufficient nutrition requires adequate availability and intake of all three macronutrients. Impacts of insufficient protein and energy intake can often be difficult to decouple, and are often termed protein-energy malnourishment (PEM)—PEM has a number of negative consequences including reduced physical and mental development (Kar, Rao and Chandramouli, 2008); increased susceptibility to disease and infection; poorer recovery and increased mortality from disease; and lower productivity (Schaible and Kaufmann, 2007). Our results indicate that India's self-sufficiency model—a reliance on domestic crop yield increases and waste reduction strategies—will be insufficient to meet requirements across all three macronutrients. Levels of undersupply and consequent malnutrition would show a significant increase in both 2030 and 2050 scenarios.

This has important implications for forward planning to effectively address malnutrition. Policy incentives in Indian agriculture since the Green Revolution have predominantly been focused on achieving caloric food security through increased production of cereals (wheat and rice) (Kadiyala *et al.*, 2014). This has resulted in a heavily carbohydrate-based diet (> 65-70% total energy intake (Misra *et al.*, 2011)) which may be significantly lacking in adequate diversity for provision of other important nutrients (Vecchio *et al.*, 2014). Widespread lactovegetarian preferences have further reduced the scope for dietary diversity (Remedios *et al.*, 2016).

If trying to address caloric inadequacy alone, efforts to increase output of energy-dense crops (i.e. cereals, roots and tubers) may seem appropriate, and has largely been India's focus to date (Varadharajan, Thomas and Kurpad, 2013). Our analysis, however, strongly suggests the need to shift dietary composition away from reliance on carbohydrates towards a more diversified intake of protein and fats (with diversification also contributing to a reduction in micronutrient deficiency) (Biol and

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[1] Based on calculations using FAOstats global crop production data and nutritional composition factors, in 2011 world crop production totalled 1.34×10^{16}kcal; 3.62×10^{14}g digestible protein; and 3.33×10^{14}g fat. 2011 Indian production amounted to 1.44×10^{15}kcal; 3.27×10^{13}g digestible protein; and 3.93×10^{13}g fat.

Prog, 2015). Forward planning therefore needs to simultaneously address caloric inadequacy and malnourishment through balanced, increased supply and intake of high-quality proteins and fats.

Our examination of macronutrient supply in India indicates large inequalities in availability across the population. This is likely to be closely coupled to the high levels of income inequality and poverty which remain in India today (Varadharajan, Thomas and Kurpad, 2013). Large inequalities in food supply and dietary intake will make it increasingly difficult for India to address its malnutrition challenges; our assessment of potential improvement scenarios highlight that, even in cases where average macronutrient supplies meet requirements, the high CV in distribution still leaves a large proportion of the total population at risk of malnourishment. To meet SDG2 (whereby all individuals' requirements are met) at current levels of inequality, the national mean intake would have to increase to 3600kcal pppd; 82g pppd digestible protein; and 105g pppd fat. This is well above current pppd supply values, even for the crop production-phase level at the top of the food system.

Inequality and poverty reduction will therefore play a pivotal role in achieving food security for all. The reliance on agriculture for employment and income for a large share of the Indian population (World Bank, 2017) means that agricultural policy and development has the ability to address both simultaneously. Agricultural policy and strategy planning affect two key macroeconomic factors; farm-level income and food commodity prices (Kadiyala *et al.*, 2014). Both of these variables have the potential to influence household purchasing power and food security.

Greater emphasis must therefore be placed on aligning agricultural and economic strategies to increase farm income (thereby increasing food expenditure), and reducing relative prices of items such as pulses, oilseeds, fruit and vegetables, and livestock products, which have typically been too expensive for those at the lower end of the income spectrum (9, 37). Doing so would allow both for increased quantity and for diversification of food supply and intake within poorer demographics—an important target for easing the national food security challenge.

Our results highlighted several key points:

- production quantities at the farm level are very low relative to global average production;
- low import and export values produce an approximately balanced trade model; this correlates with India's self-sufficiency focused agricultural and food policies;
- harvesting, post-harvest and distribution losses in the supply chain form a large proportion of total food system inefficiencies;
- a moderate amount of energy and fat (but not protein) is allocated to non-food uses, although this is significantly less than global average non-food allocation;
- India's caloric and protein losses in the conversion of edible crops to livestock are small due to the dominance of pasture-fed livestock such as dairy cattle. The large nutritional gains achieved through increased milk consumption in India suggest this may be a beneficial trade-off in agricultural land for provision of high-quality protein.

Our examination of the food supply chain in India identified harvesting, handling and storage losses, and top-level crop production to be the key intervention phases for improving food security. The approach not only adds value in the identification of 'hotspots' of wastage and inefficiency, but also allows for an understanding of the magnitude of change required to produce a certain food supply chain-wide result. Our analysis highlighted that, despite being an important mechanism for improving food security, even a 50% reduction in food loss/waste (a challenge that is achievable but would take significant economic, infrastructural and educational investment) alone would be largely insufficient in ensuring food security in India.

Increased production at the agricultural level must therefore be a focus for both near and long-term food security. The viability of achieving yields close to 75% AY in the near-term (to 2030), across the range of available crops, needs to be more closely considered. For several staple crops, a yield increase upwards of 30% and 50% would be required for attainment of 75% and 90% AY, respectively (see Supplementary Table 2). The challenge in reaching close to 90% AY (i.e. almost maximum yield) is substantial; many developed countries have not yet reached such levels (Mueller *et al.*, 2012).

The potential resource limits and environmental implications needed to achieve such yields also need to be given consideration in order to optimise crop selection and mitigate negative impacts. The yield gap could predominantly be closed through improved water and nutrient management (Mueller *et al.*, 2012). Depleting groundwater resources through agricultural irrigation in India raises key concerns over long-term water security (Mekonnen and Hoekstra, 2016)(Gupta and Deshpande, 2004), and whether water availability is likely to impose a resource limit on yield attainment. Improved yields through increased fertiliser application raise similar sustainability concerns; nitrous oxide (N_2O) is a key source of greenhouse gas (GHG) emissions, a major source being microbially-mediated emissions as a result of nitrogen fertiliser application to agricultural soils (Reay *et al.*, 2012). There may therefore be a significant GHG penalty in closing the current yield gap.

It should be noted that this study has considered only yield improvements through traditional crop varieties. Genetic variation and modification of crop strains may offer further potential for yield increases, in addition to increased resilience to pests, disease and climatic impacts (Carpenter, 2010). However, with the exception of Bt Cotton, genetically modified (GM) crop varieties are banned from commercial crop production (Kumar, 2015). Despite the introduction of GM field trials in recent years, they continue to face significant resistance across a range of stakeholder groups (Giri and Tyagi, 2016).

Our analyses for 2050 highlight severe food security challenges for India, even in scenarios which assume attainment of 90% AY for all crops. In addition to the hotspots identified for further focus to achieve near-term improvements, long-term strategies require increased consideration of the impact of potential climatic changes. India's staple crops – wheat and rice - show particular vulnerability; in the near-term, CO_2 fertilisation may offer some positive yield impacts, however, simulated climate models suggest this effect is likely to be cancelled out if global mean temperature increase reaches a 3°C threshold in wheat (2°C for rice) (Lal *et al.*, 1998). This suggests negative climate impacts may only begin to arise from mid-century onwards. Failure to build capacity and agricultural resilience in the interim could result in severe food deficits should a 2°C or 3°C warming threshold be breached. Planning strategies should therefore not only aim to adapt to gradual near-term impacts of a changing climate, but importantly focus on capacity-building for a resilient food system in a warmer post-2050 world.

Our 2050 scenarios are based on assumptions which are sensitive to change; we have assumed BAU climatic-yield factors, and increased meat and dairy intakes in line with FAO projections. Both of these assumptions could change based on global GHG mitigation progress, and governmental or social interventions on meat consumption. In addition, it is recognised that some potential climatic impacts could be reduced through shifts in crop production regions and seasonal cropping patterns

(Mall *et al.*, 2006). While such changes may marginally change the scale of the food supply and malnutrition challenge, the overall conclusions remain the same. Climatic and livestock impacts may serve to exacerbate the issue, however, India would continue to face a severe risk of widespread malnutrition regardless of these additional pressures.

This analysis has attempted to broaden the lens of nutritional food security beyond energy intake (kilocalories) to more fully consider the three major macronutrients: calories, protein and fat. However, micronutrient supply and deficiency is also of great concern across many developing countries (Ramakrishnan, 2002). Inadequate food intake, lack of dietary diversity and lactovegetarian preferences put India at significant risk of widespread micronutrient malnourishment (Mark *et al.*, 2016).

Although this study aimed to account for some elements of protein quality by correcting for digestibility, further analysis of essential amino acid (AA) production and distribution would be of significant value (this has been covered in a follow-up paper- Ritchie et al. in review). Lysine in particular has been highlighted as the key limiting AA in the Indian diet (Swaminathan, Vaz and Kurpad, 2012). Developing a better understanding of both micronutrient and AA pathways would be of significant benefit; agricultural and nutritional policies could then take a more holistic and integrated approach to addressing macro- and micronutrient malnutrition alike.

5. Conclusion

To deliver effective recommendations for addressing macronutrient undersupply and malnutrition, two key components need to be further explored. Firstly, there needs to be better understanding of optimal crop selections to maximise production and consumer supply of energy, digestible protein and fats alike. This has to be analysed with key resource and environmental constraints in mind to deliver a more optimal and sustainable domestic food system. This should include consideration of options outwith traditional domestic agricultural practice, such as genetic modification, industrial biotechnology and biofortification (Uzogara, 2000; Qaim and Kouser, 2013).

Secondly, India's role within global food markets needs to be more closely assessed. To successfully address malnutrition, India will likely have to fill the gap between domestic production and food demand through increased imports. Food imports can have a significant impact on domestic prices, and the dominance of agriculture as a primary source of employment in India may be a negative influence on farmer livelihoods (Kadiyala *et al.*, 2014); and further, a large increase in food imports could potentially reduce energy-protein intake for the poorest 30% of the population (Panda and Ganesh-Kumar, 2009). This means appropriate economic and social analysis must be carried out to try to optimise import quantities and products which will have minimal domestic impacts. The importance of reducing economic and dietary inequalities makes this even more crucial.

In order to ensure a resilient food system, such analyses and recommendations should be made alongside consideration of potential climatic impacts in the medium- and long-term. This would allow for appropriate choices to be made in the near-term that are also sustainable in a changing climate. The implications of our analysis for health, social, and environmental policy is discussed in detail in our Supplementary Discussion.

Closing its current food supply and nutrition gap while meeting increasing population demand will require a combination of domestic measures to improve agricultural practice and subsequent yields, in addition to a well-planned increase in food imports.

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Chapter Four:

Quantifying, Projecting and Addressing India's Hidden Hunger

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Abstract

It is estimated that more than two billion people suffer from 'hidden hunger' (micronutrient malnutrition) globally, with nearly half living in India. Despite being highlighted as one the most cost-effective investments for human development, progress on addressing micronutrient deficiencies (MiND) has been slowing. The severe social, health and economic costs of MiND in India should make it a top priority for domestic governance and international donors alike. Here, for the first time, we have mapped food system pathways from crop production through to household-level food availability, for a range of key vitamins, minerals and amino acids. This allowed for 'MiND by micronutrient' scenario analysis to 2030, to identify potential intervention points in the food system and the capacity of these interventions to address deficiency. Our results suggest widespread (>80% total Indian population) risk of deficiencies in calcium, vitamin A, B_{12}, folate, in addition to lysine limitation, with more localised deficiencies (<25% population) in iron, zinc, and vitamin B_6. Scenario analysis to 2030 and 2050 indicates that, although increased availability of animal-based products, reduction of supply chain losses, and close to maximum (90%) attainable yields could make some contribution to addressing Indian MiND, additional intervention strategies will be essential. Recommendations for intervention in the short (urgent), near-term (2030) and long-term (2050) have been formulated based on this analysis.

1. Introduction

1.1 India's 'hidden hunger' challenge

It is estimated over two billion people – more than one-in-three – suffer from micronutrient deficiencies globally (FAO 2013). Micronutrient deficiency (also known as 'hidden hunger' and hereafter denoted as 'MiND') occurs when the intake or absorption of essential vitamins and minerals falls below levels necessary for growth and development in children, and maintenance of physical and mental functionality in adults (von Grebmer et al. 2014).

Nearly half of the world's MiND population live in India (USAID OMNI 2005). Approximately 74% of children are at risk of anaemia as a result of iron deficiency, with 62% and 31% at risk of vitamin A and iodine deficiency, respectively (FAO 2013). Deficiencies in pregnant and lactating women in India are equally alarming—although figures vary by source, most estimate a prevalence of anaemia above 60% and in some cases, more than 80% (Varadharajan et al. 2013).

Such deficiencies during pregnancy and in childhood years lead to a range of severe implications including increased mortality, morbidity, physical and mental defects. Coupled with prevalence of energy-protein malnutrition, India has one of the highest rates of childhood stunting in the world, occurring in approximately half of all children (FAO 2013). The subsequent health and productivity costs of MiND in the adult population also result in severe economic losses; it's estimated that economic losses from MiND in India alone could amount to approximately 2.4% of its gross domestic product (GDP) (Stein & Qaim 2007).

Although progress has been made in addressing MiND in recent years, improvements in South Asia have been too slow to meet Millennium Development Goal (MDG) targets. If current trends continue, SDG2 (achieving Zero Hunger) will also be missed by 2030 (United Nations 2016). The performance of India in particular – as a result of its large, and growing, population share – will have a major bearing on the progress of the region overall.

With a projected population increase to 1.6 billion by 2050 (United Nations 2015), India faces a continued challenge both in closing the current nutrition gap, and in ensuring adequate food supply to a growing population. However, continued policy focus towards higher staple crop production is likely to fail in simultaneously addressing macro- and micronutrient malnutrition (von Grebmer et al. 2014).

1.2 Developing informed food system interventions

An efficient and complete food system is necessary to deliver all basic nutritional requirements. Although increasing agricultural production will be a core component in addressing malnutrition in India, alone it may be insufficient to provide adequate micronutrient supply. Recommendations on the capacity of agricultural and alternative strategies for addressing such 'hidden' malnutrition might be improved through a holistic analysis of micronutrient production, pathways through the food value chain, and the resultant availability of micronutrients at the household level.

As such, we have here attempted to map the flow and pathways of key micronutrients, from crop production to residual food availability within the Indian food system, in order to assess the current and future risk of MiND across the population. Our analysis also aims to explore the capacity to address identified deficiency risks through broad-based food system strategies.

2. Methods

2.1 Food system quantification of current Indian micronutrient deficiency risk

The Indian food system was mapped from crop production through to residual food availability using FAO Food Balance Sheets (FBS) from its FAOstats databases (Food and Agriculture Organization 2001). FBS provide quantitative data (by mass) on production of food items and primary commodities, and their utilisations throughout the food supply chain. Food Balance Sheet data for 2011 have been used, these being from the most recent full dataset available.

FBS provide mass quantities across the following stages of the supply chain: crop production, exports, imports, stock variation, resown produce, animal feed, other non-food uses, and food supplied (as kg per capita per year). Data on all key food items and commodities across all food groups (cereals; roots and tubers; oilseeds and pulses; fruit and vegetables; fish and seafood; and meat and dairy) are included within these balances. While there are uncertainties in FAO data (see Supplementary Information for further discussion on FAO data limitations), FBS provide the only complete dataset available for full commodity chain analysis. Therefore, while not perfect, they provide an invaluable high-level outlook of relative contribution of each stage in the food production and distribution system.

In order to calculate the total nutritional value at each supply chain stage, commodity mass quantities (e.g. tonnes of wheat) were multiplied by micronutrient contents from the South Asian FAO INFOODS composition and USDA nutrient databases (FAO 2016; USDA 2016).The summation of micronutrient production across all commodities at each stage allows us to build a waterfall pathway of total micronutrient production, losses, re-allocation and wastage down to the household availability level.

This study attempts to quantify the average supply and availability of micronutrients through the commodity chain—micronutrients can additionally be lost through processes such as cooking. These latter losses are difficult to quantify and, as such, we consider our results to be an upper estimate of micronutrient availability at the point of consumption.

In this analysis, the key vitamins and minerals necessary for human health were assessed, including iron, zinc, calcium, vitamins A, B_6, B_{12}, and folate. The concentration of iodine in food items is highly variable, and strongly dependent on soil properties (Miller & Welch 2015). This makes it challenging to assess iodine pathways using this approach; iodine quantification has therefore been omitted from this study.

Protein quality is a key concern for India in particular as a result of its largely grain-based diet (Ritchie et al. 2017), with grains tending to have poorer digestibility and amino acid (AA) profiles than animal-based products and plant-based legume alternatives (Swaminathan et al. 2012),(Wu 2016). In addition to mapping vitamin and mineral pathways, we have also analysed the pathways of all indispensable amino acids (FAO 2011a) using FAO and USDA composition databases (FAO 2016;

USDA 2016). Amino acids (AAs) are presented as the quantity per gram of protein (mg/g protein), rather than in absolute terms.

FBS do not provide food loss and waste figures by stage in the supply chain. Food loss figures have instead been estimated based on regional percentages provided in separate FAO literature (FAO 2011b). These percentage figures break food losses down across seven commodity groups and five supply chain stages (agricultural production, postharvest handling and storage, processing and packaging, distribution and consumption). The applied percentage values by commodity type and supply chain stage are provided in Supplementary Table 1.

For consistency, and to provide a better understanding of the food system down to the individual level, all metrics have been normalised to average per person per day (pppd) availability using UN population figures and prospects data (United Nations 2015). Whilst this provides an average per capita value for availability, it does not account for variability of micronutrient supply within the population. To help adjust for this, we have also estimated the assumed distribution of supply of each micronutrient using the FAO's preferred log-normal distribution and India-specific coefficient variation (CV) factor of 0.26 (FAO 2014). Whilst the requirements for and intakes of micronutrients vary across demographic groups—depending on age, gender, activity levels, and pregnancy— we believe this method of estimation is appropriate and is in line with the standardised Estimated Average Requirement (EAR) cut-point method, described below.

The number of individuals at risk of deficiency for micronutrients and amino acids were quantified using the Estimated Average Requirement (EAR) cut-point method (Institute of Medicine 2005). The EAR is defined as the median required intake and is based on the assertion that nutrient intake and requirements are independent; the distribution of requirements falls symmetrically around the EAR value; and the distribution of nutrient intakes is much larger than that of requirements (World Health Organization 2005). WHO guidelines for calculation of Indian population EARs (for individuals >12 months of age) have been followed using specific demographic weightings for India (Mark et al. 2016; Narasinga Rao 2010; World Health Organization 2005). Full data on EARs by age and gender group, and India population weightings are provided in S2-4 Tables. The proportion of the population defined as 'at risk of deficiency' was subsequently calculated as those where estimated availability was below the India-specific weighted EAR for each vitamin, mineral and amino acid.

2.2 Projected 2050 deficiencies under business-as-usual (BAU) conditions

To assess whether India's micronutrient deficiency risks would decrease through time as a result of expected increases in meat and dairy intake, and continued crop yield improvements under business-as-usual policy support, our initial analysis (for 2011) was first re-assessed to estimate potential levels of MiND in 2050.

It is projected that, through economic growth and shifts in dietary preferences, meat and dairy demand in India will continue to increase through to 2050. It was therefore assumed that per capita demand in 2050 is in line with FAO projections: this represents an increase in meat from 3.1kg per person per year (2007) to 18.3kg in 2050, and an increase in milk and dairy from 67kg to 110kg per person per year (Alexandratos & Bruinsma 2012).

Crop yield improvements were derived based on closure of current farm yields (FY) to reported attainable yields (AY). FY is defined as the average on-farm yield achieved by farmers within a given region, and AY is defined as the economically attainable (optimal) yield which could be achieved if best practices in water and pest management, fertiliser application and technologies are utilised in non-nutrient limiting conditions. Crop yield increases were therefore derived assuming closure of this yield gap to 90% of AY based on published Indian crop-specific figures (Mueller et al. 2012). These data are available across all key crop types (see Supplementary Table 5 for baseline, and AY values). Note that this study is based on traditional crop varieties and has not included potential genetic variation and modification varieties, which are currently not consented in India (with the exception of Bt Cotton) (Kumar 2015).

Climate change impacts on crop yields in India remain highly uncertain; the importance of temperature thresholds in overall crop tolerance makes yield impacts highly dependent on greenhouse gas emission scenarios (Lal et al. 1998). This makes it challenging to robustly project 2050 climate change impacts. As such, we applied average percentage changes in yields of Indian staple crops based on meta-analysis review (Mall et al. 2006) of field-based observations and climate model results. The studies utilised present results for a doubling of atmospheric CO_2 from pre-industrial levels. This approximates to a business-as-usual (BAU) scenario for 2050 (IPCC 2014). The yield-climate factors applied in this analysis are provided in Supplementary Table 6.

To best demonstrate the food production potential of current agricultural support mechanisms, such as governmental policy and subsidy (which largely determine crop choices), the relative allocation of crop production was assumed constant. It was also assumed that production increases were achieved through agricultural intensification alone; this assumption was based on FAOstats data which has shown no increase in agricultural land area over the past decade, indicating a stagnation in agricultural extensification. To correct for 2050 population estimates, all metrics were re-normalised to 'per person per day' (pppd) based on medium fertility scenario projections from the UN prospects (United Nations 2015).

2.3 Accelerated intervention strategies to 2030

If India is to meet the SDG2 targets of ending malnutrition (i.e. by 2030), these strategies will likely have to be accelerated. To assess the impact of strategic acceleration of food production and waste interventions to meet SDG2 in the context of micronutrient supply, four hypothetical scenarios were assessed. As for the 2050 scenario, all metrics were re-normalised to 'per person per day' (pppd) in 2030 based on medium fertility scenario projections from the UN prospects (United Nations 2015).

The following scenarios were assessed:

Scenario 1: increased meat and dairy intake. This scenario assumes that the FAO's average projected meat and dairy intake in 2050 was reached by 2030 (Alexandratos & Bruinsma 2012). This scenario assumes no change in supply chain losses or increases in crop production.

Scenario 2: 50% reduction in supply chain losses. This scenario assumes that harvesting, post-harvest, processing and distribution food losses were reduced by 50%. This scenario assumes no change in meat and dairy consumption, or crop production.

Scenario 3: increased meat and dairy intake, and attainment of 90% attainable yields (AY). This scenario combines Scenario 1 with significant improvements in crop yields to close the current yield gap to 90% of attainable yields (AY). This scenario applies the methodology implemented in the 2050 business-as-usual analysis, with adjustment in line with a smaller population in 2030.

Scenario 4: increased meat and dairy intake, 50% reduction in supply chain losses and attainment of 90% attainable yields (AY). This scenario assesses the combined impact if all measures were implemented, thereby assessing the maximum capacity of broad-based strategies to address MiND by 2030.

3. Results

3.1 Current micronutrient malnutrition

Following full pathway analysis from crop production through to individual intake, average Indian intakes in 2011 are shown in Table 1 for the key micronutrients and amino acids. By estimating the national distribution of intakes, the percentage of the total population and equivalent number of individuals falling below Estimated Average Requirements (EARs—see Methods) are also shown. These individuals are subsequently considered to be at risk of MiND or lysine limitation. A coloured 'traffic light' system has been employed in Table 1, where red indicates a risk of deficiency in >50% of the population; orange for 25-50%; yellow for <25%; and green for <5% risk of deficiency.

Our results indicate severe deficiencies across all key micronutrients for the Indian population in 2011. These deficiencies broadly fall into two categories (which are important to differentiate for more effective intervention strategies): 'nationwide deficiencies' where the majority of the population are at risk; and 'targeted deficiencies' where a smaller and more specific demographic of the population fall below requirements.

In our analysis, iron, zinc and vitamin B_6 could be considered to be targeted deficiencies with 41%, 25% and 6% of the population falling below EARs, respectively. It's likely that children, women, and more specifically pregnant or lactating women, will be the dominant demographics within these groupings as a result of unequal access to good nutrition and healthcare, and higher typical requirements (see Supplementary Tables 3-4 for EARs by demographic). Although iron and B-vitamin deficiencies do not result in anaemia in all cases, they can act as an important precursor (Lynch 2011). High incidences of anaemia in pregnant women and children in India (Varadharajan et al. 2013) further suggest that these groups are likely to dominate the specific demographic at risk of deficiency.

The other key micronutrients assessed - calcium, vitamin A, B_{12} and folate – all indicate a widespread risk of deficiency, with 94%, 89%, 89% and 81% at risk, respectively. An overall lack of dietary diversity, particularly with respect to fruits, vegetables, pulses and animal-based products is likely to be responsible for nationwide risk of MiND with respect to these micronutrients (von Grebmer et al. 2014).

	Iron (mgpppd)	Calcium (mgpppd)	Zinc (mgpppd)	Vitamin A (µgpppd)	Vitamin B_6 (mgpppd)	Vitamin B_{12} (µgpppd)	Folate (mgpppd)
Estimated Average Requirement (EAR)	14	639	9.6	402	1.0	1.8	298
Average Availability (2011)	15	463	12	308	1.7	1.4	245
Risk of deficiency, % of population (number of people)	41% (509m)	94% (1167m)	25% (316m)	89% (1112m)	6% (73m)	89% (1112m)	81% (1007m)

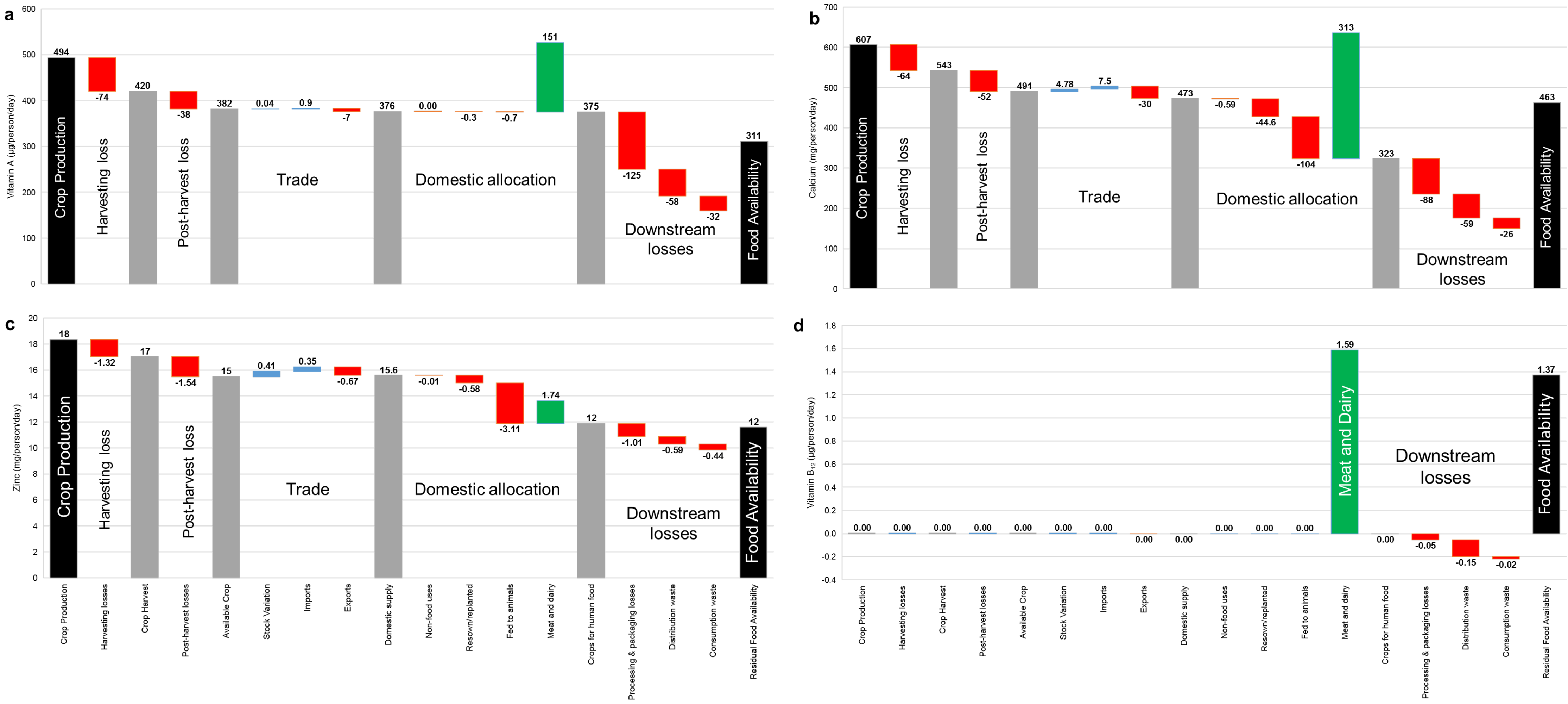
	Isoleucine (mg/g protein)	Leucine (mg/g protein)	Lysine (mg/g protein)	Methionine +Cysteine (mg/g protein)	Phenylalanine + Tyrosine (mg/g protein)	Threonine (mg/g protein)	Tryptophan (mg/g protein)	Valine (mg/g protein)	Histidine (mg/g protein)
Estimated Average Requirement (EAR)	30	60	46	23	39	24	6	40	16
Average Availability (2011)	38	58	41	33	78	30	10	46	22
Risk of deficiency, % of population (number of people)									

Table 1: Average per capita intake of key micronutrients and essential amino acids assuming equitable distribution in India (2011). Average per capita intake of essential vitamins and amino acids in India assuming an equitable distribution across the population, measured in 2011. These are measured versus the national weighted estimated average requirement (EAR). Also noted is the percentage and absolute number of the population at risk of deficiency based on distribution curves. A coloured 'traffic light' system has been employed, where red indicates a risk of deficiency in >50% of the population; orange for 25-50%; yellow for <25%; and green for zero risk of deficiency.

Our amino acid results indicate that lysine, and less notably leucine, are limiting in the average Indian diet, falling below EAR values. This strongly supports previous studies which have highlighted lysine as a major concern for protein quality, especially in low-meat diets (FAO 2011a; Swaminathan et al. 2012).

Analysis of how micronutrient pathways evolve from crop production to human consumption plays an important role in understanding potential intervention points. There is significant variability in overall pathway patterns between the various micronutrients analysed in this study. Vitamins and minerals concentrated in highly perishable foods, such as fruits, vegetables and animal-based products, show proportionately higher supply chain losses versus macronutrients (FAO 2011b).

Distribution in Vitamin A, zinc and B_{12} have been used here to demonstrate the contrast in pathways for nutrients concentrated in fruit and vegetables, cereal-based, and animal-based produce. For example, almost 70% of plant-based vitamin A is lost between crop production and food availability (Figure 1a), with minerals such as calcium (Figure 1b) showing similar loss streams. Both show significant losses at post-harvest, processing and distribution stages. This is in contrast to minerals more concentrated in less perishable commodities; for example, zinc, which is more concentrated in cereals, beans, and nuts in the Indian diet, shows lower processing and distributional losses (Figure 1c). The pathways for elements unique to meat and dairy products - such as vitamin B_{12} have a significantly shorter value chain, and are largely determined by total meat production (Figure 1d). Full pathways for all micronutrients are provided in Supplementary Figures 1a-g.



Figures 1a-d: Production and losses in the Indian food system from 'field to fork' in 2011. Food pathways in (a) vitamin A; (b) calcium; (c) zinc; (d) vitamin B_{12} from crop production to food eaten, normalised to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate micronutrient availability at intermediate stages of the chain.

3.2 Long-term (2050) deficiencies under business-as-usual (BAU) conditions

Full results (including average intake, risk of deficiency, and coloured representation) in the case of a business-as-usual agricultural policy and expected (FAO) meat intake to 2050 are provided in Table 2.

In almost all micronutrients and amino acids, there is a reduction in the percentage of the population at risk of deficiency by 2050 compared to current (2011) levels. This improvement in average intake is sufficient to progress vitamin B_{12} from a red to amber rating, and an elimination of leucine limitation in the average diet. However, severe deficiencies in all micronutrients remain, and lysine continues to be limiting.

It is worth noting that, despite significant reductions in the percentage of the population at risk of deficiency by 2050, the absolute number of individuals at risk increases in most cases as a result of Indian's growing population.

3.3 Accelerated intervention strategies to 2030

Results of the four scenarios mapped through to 2030 are shown in Table 3, with comparison to EAR and current (2011) values. Our results show that under no scenario—even scenario 4, where all three broad-based strategies are combined—are deficiencies in any of the key vitamins and minerals sufficiently addressed. However, comparison of the four scenarios is valuable in informing the relative merits of each of the individual interventions, and in exploring what additional measures would be necessary to sufficiently address this challenge.

	Iron (mgpppd)	Calcium (mgpppd)	Zinc (mgpppd)	Vitamin A (µgpppd)	Vitamin B_6 (mgpppd)	Vitamin B_{12} (µgpppd)	Folate (mgpppd)	Isoleucine (mg/g protein)	Leucine (mg/g protein)	Lysine (mg/g protein)	Methionine +Cysteine (mg/g protein)	Phenylalanine + Tyrosine (mg/g protein)	Threonine (mg/g protein)	Tryptophan (mg/g protein)	Valine (mg/g protein)	Histidine (mg/g protein)
Estimated Average Requirement (EAR)	14	639	9.6	402	1.0	1.8	298	30	60	46	23	39	24	6	40	16
Average Availability (2050)	15 *39% (639m)*	528 *77% (1250m)*	12.5 *15% (245m)*	369 *63% (1026m)*	1.7 *3% (42m)*	1.8 *50% (803m)*	253 *74% (1197m)*	47	68	42	24	88	35	14	56	26

Table 2: Average per capita intake of key micronutrients and essential amino acids assuming equitable distribution in 2050. Average per capita intake of essential vitamins and amino acids in India assuming an equitable distribution across the population in 2050 projections based on business-as-usual agricultural policies. These are measured versus the national weighted estimated average requirement (EAR). Also noted is the percentage and absolute number of the population at risk of deficiency based on distribution curves. A coloured 'traffic light' system has been employed, where red indicates a risk of deficiency in >50% of the population; orange for 25-50%; yellow for <25%; and green for zero risk of deficiency.

Analysis of amino acid limitation highlights that, in all scenarios where expected 2050 meat and dairy intake is accelerated to 2030, lysine is no longer considered limiting in the average Indian diet. Note that many individuals will still be consuming less than the average meat intake—for these individuals, lysine, and possibly leucine, limitation would still continue to affect protein quality. The necessity of increased meat and dairy intake for amino acid provision is emphasised by continued lysine and leucine limitation in scenario 2, where supply chain losses are reduced but per capita consumption of animal-based products remains at current (2011) levels.

As results from scenario 2 show, a significant reduction in supply chain losses is significant in improving availability of vitamin A. This would be expected from food pathway results presented in current malnutrition results, where the loss of perishable commodities, such as fruits and vegetables, resulted in significant losses of vitamin A from the supply chain. Folate, another vitamin richly concentrated in fruits and vegetables, also showed significant improvement (albeit insufficient to reduce risk of MiND below 50%). Improved supply chain management alone, without increased crop yields and meat intake, would naturally result in an increase in deficiencies of the remaining vitamins and minerals as a result of a growing population.

The key contribution of an accelerated increase in meat and dairy intake (scenario 1) is an increase in vitamin B_{12} consumption, as meat and seafood are the only natural dietary source of B_{12}. Vitamin A intake also improves with increased meat and dairy consumption, although this is less effective than a reduction in supply chain losses.

A combination of increased meat and dairy, significant increases in crop yields, and reduced supply chain losses (scenario 4) would result in the largest reductions in MiND. All deficiencies, with the exception of calcium, would fall below 50%. Risk of deficiency in iron, zinc and vitamin-B_6 would see significant reductions - all below 10% of the population. However, levels of MiND in calcium, folate and vitamins A and B_{12} would remain severe.

	Iron (mgpppd)	Calcium (mgpppd)	Zinc (mgpppd)	Vitamin A (µgpppd)	Vitamin B_6 (mgpppd)	Vitamin B_{12} (µgpppd)	Folate (mgpppd)	Isoleucine (mg/g protein)	Leucine (mg/g protein)	Lysine (mg/g protein)	Methionine +Cysteine (mg/g protein)	Phenylalanine + Tyrosine (mg/g protein)	Threonine (mg/g protein)	Tryptophan (mg/g protein)	Valine (mg/g protein)	Histidine (mg/g protein)
Estimated Average Requirement (EAR)	14	639	9.6	402	1.0	1.8	298	30	60	46	23	39	24	6	40	16
Scenario 1 (2030): *Increased meat and dairy intake*	10.3 *89%* *(1353m)* 🔴	453 *91%* *(1391m)* 🔴	9.5 *52%* *(789m)* 🔴	373 *62%* *(943m)* 🔴	1.4 *12%* *(182m)* 🟡	1.7 *58%* *(892m)* 🔴	223 *87%* *(1331m)* 🔴	41 🟢	65 🔴	52 🔴	34 🟢	78 🟢	33 🟢	11 🟢	49 🟢	25 🟢
Scenario 2 (2030): *50% reduction in post-harvest and supply chain losses*	12 *73%* *(1111m)* 🔴	463 *90%* *(1368m)* 🔴	9.4 *53%* *(814m)* 🔴	403 *50%* *(762m)* 🟠	1.5 *7%* *(112m)* 🟡	1.3 *90%* *(1369m)* 🔴	273 *63%* *(968m)* 🔴	33 🟢	52 🔴	36 🔴	27 🟢	65 🟢	26 🟢	8 🟢	40 🟢	19 🟢
Scenario 3 (2030): *Increased crop production (90% AY) and increased meat and dairy intake*	17 *22%* *(343m)* 🟡	543 *74%* *(1126m)* 🔴	13.5 *9%* *(139m)* 🟡	374 *61%* *(937m)* 🔴	1.9 *1%* *(13m)* 🟡	1.7 *58%* *(892m)* 🔴	277 *61%* *(935m)* 🔴	50 🟢	79 🟢	63 🟢	42 🟢	97 🟢	41 🟢	13 🟢	60 🟢	31 🟢
Scenario 4 (2030): *Increased crop production (90% AY), increased meat and dairy intake and waste reduction*	19.8 *9%* *(135m)* 🟡	629 *52%* *(800m)* 🔴	15.3 *3%* *(52m)* 🟡	449 *33%* *(512m)* 🟠	2.2 *0.2%* *(2m)* 🟡	1.8 *50%* *(757m)* 🟠	341 *30%* *(456m)* 🟠	49 🟢	77 🟢	61 🟢	36 🟢	84 🟢	35 🟢	12 🟢	52 🟢	27 🟢

Table 3: Average per capita intake of key micronutrients and essential amino acids assuming equitable distribution under 2030 scenarios. Average per capita intake of essential vitamins and amino acids in India assuming an equitable distribution across the population in 2030 based on meat, waste and yield scenarios. These are measured versus the national weighted estimated average requirement (EAR). Also noted is the percentage and absolute number of the population at risk of deficiency based on distribution curves. A coloured 'traffic light' system has been employed, where red indicates a risk of deficiency in >50% of the population; orange for 25-50%; yellow for <25%; and green for zero risk of deficiency.

4. Discussion

Our results indicate that the current risk of 'hidden hunger' in India is severe. This has been previously acknowledged within the literature (Klaus von Grebmer, Jill Bernstein, Nilam Prasai, Shazia Amin 2016), however the true extent of this risk across key micronutrients has been poorly quantified. The novel mapping of pathways of micronutrients, from crop production through to availability at the household level, undertaken here provides a valuable tool in highlighting the potential leverage points in the supply chain which could be used to address these deficiency risks.

Analysis of business-as-usual pathways to 2050, and accelerated intervention strategies to 2030, highlight that, while increased meat and dairy intake, increased crop production and a reduction in supply chain losses have the potential to reduce the prevalence of MiND, they will be insufficient alone—even in the most optimistic scenarios—to meet the target of SDG2 by the target date of 2030, or even 2050.

4.1 Broad-based strategies

It's important to note the scale of the challenge India would face in accelerating these three broad-based strategies to 2030 as envisaged here. The potential contribution and challenges of each of these options are described below.

Increased meat and dairy intake: Animal-based products are described as 'complete proteins', having adequate proportions of all essential amino acids (meaning none are considered to be 'limiting'). In addition to being a key source of high-quality protein, meat is rich in iron, zinc and B-vitamins; dairy products form a key source of calcium, B_{12}, vitamin A and folate (Rivera et al. 2003). Animal products are the only natural source of vitamin B_{12}. Their consumption has shown additional nutritional benefits beyond those expected from increased micronutrient provision alone; studies have linked their consumption to increased bioavailability and absorption of iron and zinc from other food groups when consumed together (Welch 2001).

There is significant agreement that moderate consumption of animal-based produce is particularly important for children, leading to improved growth outcomes, including improved cognition and motor performance (Dror & Allen 2011). Studies across a number of low-income countries in Africa and South Asia have suggested a strong link between meat consumption in young children and lower stunting rates (Krebs et al. 2011). As India has strong lactovegetarian preferences (Remedios et al. 2016) and one of the highest rates of childhood stunting globally (FAO 2013) this is an important consideration.

Increased meat consumption has historically been a direct reflection of economic growth (Alexandratos & Bruinsma 2012), and therefore tends to grow in line with economic trends. This makes it challenging to deliberately accelerate uptake, unless through economic mechanisms such as meat subsidisation. We suggest that, while increased meat consumption should continue to be a focus, the promotion of sustainable and nutritionally-similar alternatives such as pulses, legumes and meat-free substitutes (Kumar et al. 2017) should also be closely considered.

Pulses and legumes may offer a significantly more sustainable alternative protein and micronutrient source (with the exception of vitamin B_{12}) (Vecchio et al. 2014). The development and increasing popularity of meat-free substitute products, such as mycoprotein and in-vitro meat, may also offer sustainable proteins with a comparable nutritional profile (Apostolidis & McLeay 2016; Pandurangan & Kim 2015). The lack of market access, and current economic barriers in India mean that widespread uptake of these products is unlikely to be feasible in the short-term. However, significant progress in the biotechnology sector to reduce consumer cost and widen market penetration for such meat-free products could be a viable target; this could provide lower-cost, micronutrient-rich proteins, allowing India to 'leapfrog' the traditional development pathway of increasing meat consumption.

Reduction of supply chain losses: Supply chain inefficiencies and losses have received significant attention in their contribution to malnutrition (FAO 2011b) and environmental impacts (Porter et al. 2016). It's important to distinguish between food 'losses' and 'wastage': the former describes edible food lost at the harvesting, post-harvest, production and processing stages of the chain, whereas the latter describes wastage as a result of behavioural factors at the retail and consumer level (Bond, M., Meacham, T., Bhunnoo, R. and Benton 2013). Food system analyses in this study highlight that the majority of India's losses occur within the post-harvest, processing and distribution stages of the food chain - likely as a result of poor management, refrigeration, and preservation practices during storage and transportation. This loss is even more significant for micronutrient-rich commodities such as fruits, vegetables and animal products (Miller & Welch 2015).

The majority of developed countries have planned food processing infrastructure, which has effectively reduced the amount of upstream food loss (although this has transitioned to higher wastage at the consumer level) (FAO 2011b). Food processing in the form of packaging and preservation can significantly reduce food losses and enhance nutritional value (Miller & Welch 2015). It not only prevents overall spoilage, but also helps retain micronutrients that might otherwise be lost over time. Processing is also a pre-requisite for food fortification (discussed below), hence the two strategies go hand-in-hand.

Investment in improved management systems to prevent losses can reap multiple benefits: it improves the nutritional value of foods and subsequently contributes to reducing micronutrient deficiencies; it can allow farmers a higher income through a larger sellable harvest; and it reduces the resource inputs (water, energy, fertiliser, and resultant greenhouse gas (GHG) emissions) for a given utilisable output. The benefits of investment in food supply chain management can therefore be very significant, and reaped by a range of beneficiaries.

Our results indicate that the micronutrients with the greatest supply chain losses—vitamin A, folate, and calcium—are associated with widespread risks of deficiency (across the majority of the population in India). This signals the need for a mass intervention strategy with nation-wide coverage. India's demographic distribution currently poses important challenges to developing a country-wide food network that fully addresses MiND. Such infrastructure is often most effective through centralised distribution centres—thereby most-suited to urban populations, and rural regions with sufficient connectivity (Miller & Welch 2015). We suggest that the development of such networks in expanding urban centres should form a near-term (next 5 years) priority. Connectivity with rural populations is likely to be limited during this period, however work towards rural integration over longer timescales (>10 years) should be an ongoing and progressive priority.

Increased crop yields and production: this study assessed the impact of closure of current yield gaps to 90% of attainable yields (AY) by 2030 (scenarios 3 and 4) on MiND risks. To achieve this high level of production, India would have to significantly improve on its historical trend of staple crop yield enhancement through to 2030. For example, wheat yields in India are growing at approximately 0.9% per annum (non-compounding) from 2009 levels and have shown roughly linear growth at this rate over the last decade (Fischer et al. 2014). To attain the 90% AY figures used in this study, yields would have to increase by 36% from 2011 levels, equating to a consistent annual growth rate of 1.9% to 2030. This is double India's historical growth rate—a highly ambitious target which would require significant investment in terms of agricultural practice, irrigation and fertilisation practices.

Resource constraints in terms of soil fertility (Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D. and Gupta 2002), declining water tables (Mekonnen & Hoekstra 2016) and recent concerns over yield stagnation globally —in wheat, rice and maize in particular (Ray et al. 2012)—suggests that such progress may be technically unfeasible even with significant investment.

India's challenge of maintaining balance between macro- (calories, total protein, and fat) and micronutrient (mal)nutrition is difficult to address. India's agricultural policies are currently still oriented towards achieving self-sufficiency in calories and protein (von Grebmer et al. 2014), predominantly through favourable subsidies for rice, wheat, and sugarcane production (Sharma & Thaker 2010). Despite this drive for self-sufficiency, the prevalence of macronutrient deficiency (calories, protein and fat deficiency) remains high; domestic food production faces a serious challenge in addressing current malnutrition, in addition to keeping pace with projected population growth (Ritchie et al. 2017).

Our analysis suggests that agricultural policy orientation and land allocation towards production of staple crops may have resulted in a domestic crop composition which is insufficient to also address micronutrient needs. Crop and dietary diversification may offer one option. However, the re-allocation of land used for staple crop production towards more micronutrient-dense commodities will, in most cases, result in reduced total caloric production. This suggests an important conclusion, supported by the results from the scenarios we have considered: India's domestic agriculture will be insufficient to address both macro- and micronutrient deficiencies simultaneously.

As such, food imports could play an important role in bridging this gap. However, food imports can have a significant impact on domestic prices (Anand et al. 2016), and with the dominance of agriculture as a primary source of employment in India, a negative influence on farmer income (Kadiyala et al. 2014). Further research is therefore needed on how to best optimise global food trade and import strategies for India, without significant adverse impacts on domestic prices and livelihoods. In an optimal scenario, such trade agreements would benefit poorer rural households through increased agricultural income, thereby making dietary diversification more affordable for all demographics.

The types of commodities essential in reducing MiND vary by micronutrient (key dietary sources of each micronutrient are detailed in Supplementary Table 7). Vegetables—leafy greens in particular—are typically micronutrient-dense, with high levels of calcium, iron, zinc, vitamin-A and folate (USDA 2016). Pulses and legumes hold multiple benefits for overall nutrition in India: they possess high levels of iron, zinc, and folate, and are one of the few commodities with calcium levels comparable to dairy produce (ibid). They also offer a key source of high-quality protein (thereby contributing to overall protein malnutrition alleviation), being the few plant-based commodities rich in lysine. From a sustainability perspective, pulses and legumes have been highlighted as a core solution on transitioning towards a more sustainable food system; nitrogen-fixation in leguminous crops aid soil fertility and reduces fertiliser demands (Gliessman 2016); they also constitute one of the lowest-intensity, high-protein food groups in terms of GHG emissions (Tilman & Clark 2014), and have low water requirements relative to alternatives (Vanham et al. 2013). Whether imported or produced domestically, pulses and legumes could form an integral part of Indian dietary diversification, with a unique ability to simultaneously address MiND and protein malnutrition sustainably.

While the broad-based strategies discussed here could be integral to addressing MiND in India, policies will need to combine these strategies with additional targeted interventions (such as food fortification, biofortification and dietary supplementation). These targeted interventions are detailed by supply chain stage, description and estimated cost in Table 4, and discussed in the following section.

	Supply chain stage	Description	Estimated Cost (pppa = per person per annum)
Food fortification	Food processing level	The process of intentionally adding an essential micronutrient to a food, to improve its nutritional quality and provide a public health benefit with minimal risk to health	US$0.05pppa for salt iodisation US$0.12pppa other fortification
Biofortification	Crop production/field level	The practice of increasing the bioavailable concentration of essential micronutrients in a harvested crop through genetic selection or agronomic intervention	US$1,600,000 per year (national total) for rice in India
Supplementation	Household level	Concentrated solutions of a particular micronutrient to offer nutritional enhancement to an individual's diet (typically ingested orally as in tablet or powder-form)	US$1-1.20pppa in South Asia

Table 4: Key targeted intervention options for addressing micronutrient deficiencies in India. A brief summary of three key targeted interventions suitable for addressing micronutrient deficiency in India, with details on supply chain stage and estimated costs of implementation. Additional discussion on the relative merits and demands of targeted interventions can be found in the Supplementary Discussion.

4.2 Targeted Interventions

Our results indicate an important distinction in deficiency risk between micronutrients: iron, zinc, and vitamin B_6 deficiency is likely to be most prevalent in a particular subsection of the population—so targeted interventions which reach the affected demographics (primarily children, pregnant and lactating women) are therefore necessary. In contrast, inadequate intake of calcium, vitamin A, B_{12}, folate, and iodine are widespread—hence strategies addressing these deficiencies must be implemented across the entire population.

The selection of intervention strategy is context-dependent and determined by several key factors: the specific micronutrient being addressed; the prevalence of deficiency within a given population (i.e. widespread or demographic-specific); and the infrastructural, social and economic circumstances of the country or region in question (Miller & Welch 2015). As such, these factors must form core considerations in policy decisions—failure to do so is likely to reduce effectiveness and may result in misplaced resources.

The potential role of different intervention measures based on the results of this study, and the Indian context, are discussed below. The feasibility of each strategy for addressing MiND by micronutrient is summarised in Table 5.

4.2.1 Food processing and fortification

Food processing not only allows for a reduction of supply chain losses, but also provides the infrastructure necessary to facilitate food fortification. Food fortification is implemented at the processing stage, and involves the addition or enhancement of one or more nutrients to a food product. Several types of fortification programmes exist, covering mass, targeted, voluntary and mandatory fortification (Allen et al. 2006). Multiple programme types are relevant in the Indian context.

Mandatory fortification applies in the case where the government makes it a regulatory requirement to fortify a given food product (Allen et al. 2006). The most common case of mandatory fortification is the Universal Salt Iodisation (USI) programme—which India also implements—which requires salt to be fortified with an adequate amount of iodine (≥15ppm). The USI programme has achieved significant global success, with an estimated eradication of iodine deficiency in 34 countries, and delivery of iodised salt to more than 70% of households across the world (Unicef 2008). India has also celebrated significant success in decreasing levels of iodine deficiency (Rah et al. 2015), however progress in addressing this MiND appears to be slowing (Miller & Welch 2015).

	Dietary diversification	Increased meat and dairy (or relevant substitute)	Reduction supply chain losses	Food processing fortification	Biofortification	Dietary supplementation
Iron	x	x		x	x	x
Calcium	x	x	x	x		x
Zinc	x			x	x	x
Vitamin A	x		x	x	x	x
Vitamin B_6		x		x		x
Vitamin B_{12}		x		x		x
Folate	x		x	x		x
Iodine				x		
Lysine		x		x		x

Table 5: Suitability of the various food-based and targeted intervention options in addressing Indian deficiency, by micronutrient. The suitability of addressing population-wide and demographic-specific micronutrient deficiencies by food-based and targeted interventions. Additional discussion on the relative merits and demands of food-based and targeted interventions can be found in the Supplementary Discussion.

Iodised salt only reaches an estimated 71% of Indian households (Rah et al. 2015), falling well short of the 90% coverage required to achieve USI status. The 30% of households which are currently not receiving iodised salt are likely to be those in the most remote areas—meaning there are significant distribution and access barriers—and of low socioeconomic status. Overcoming these infrastructural challenges for full coverage should be an urgent priority, with USI being a practice which is sustained in the long-term. USI is a sustainable, cost-effective means of eradicating iodine deficiency, with an annual cost of only US$0.05 per person, and a benefit:cost ratio of 30:1 (The Micronutrient Initiative 2009).

Mass fortification involves the addition of micronutrients to particular food groups or products which are widely consumed across a given population, such as wheat or rice in India. This type of programme is used in addressing nutrient deficiencies which are prevalent across a large proportion of the population. In the case of India, this would include calcium, vitamin A, B_{12}, folate and lysine. However, this coverage could also be extended to a wider range of micronutrients, especially those such as iron and zinc where deficiency is still highly prevalent, albeit within smaller demographics. The major barrier to mass fortification is India's current lack of centralised food processing and distribution networks; these form a fundamental pre-requisite for effective mass fortification programmes. As with biofortification (described below), the financial hurdle to fortification is the capital cost involved in development of appropriate infrastructure and networks (Miller & Welch 2015). Once in place, the running costs can be very low, with a high payback ratio; wheat and flour fortification can cost just US$0.12 per person per year (The Micronutrient Initiative 2009).

We suggest that food fortification strategies should be coupled with processing developments for reduction of supply chain losses—it is recommended that this forms a near-term (next 5 years) priority, with acknowledgement that coverage is likely to be initially limited to urban populations. Connectivity and wider infrastructure networks for broader coverage should continue to be a focus over longer timescales.

4.2.2 Biofortification

Biofortification occurs at the earliest stage of the food system. It is a comparably newer strategy, involving the innovative use of plant breeding to increase micronutrient concentrations in staple crops (Bouis 2003). Despite biofortification sometimes being considered a competing strategy, it can be a well-suited complement to commercial fortification (Miller & Welch 2015). Since the two approaches are most effective in targeting different beneficiaries, they can be used simultaneously to reach a larger subset of the total population. Commercial fortification is more easily suited to urban, well-connected populations, whereas biofortification can be more effective in rural areas where food production is localised, often subsistence-driven, and poorly-connected to distribution centres.

Following the development and distribution of biofortified crop varieties, the farmer should ideally be able to sow and harvest the crop using traditional approaches (i.e. the farmer's only change would be in adopting the new seed varieties) and incur no change in relative costs. Biofortification research and development is still in its relative infancy, with efforts focused across countries in the Global South (Saltzman et al. 2013).

Crops targeted for biofortification should be staple crops commonly produced and consumed by the local population—in India, this is likely to be wheat, rice, pearl millet and sweet potato. To date, effective biofortification of crops with iron, zinc and vitamin-A has been proven, with distribution via the HarvestPlus programme (http://www.harvestplus.org/). In India, this includes zinc wheat, iron pearl millet, and 'golden rice' (vitamin-A enriched rice). Such biofortification could address the targeted deficiencies of iron and zinc—most likely to be prominent in rural pregnant women and children—and widespread vitamin-A deficiency.

The HarvestPlus programme predicts that it could take more than a decade before biofortified crops are widely distributed and utilised in target countries (Miller & Welch 2015). This suggests that increasing uptake should be a near-term intervention focus for India, but wide adoption is only likely to be achievable over the longer-term. In the meantime, we suggest that development work should focus on addressing the qualities of biofortified varieties which will increase their social acceptability: they should be equally (if not more) profitable for a farmer than current harvested varieties; harvested crops must be attractive and accepted by consumers in target markets; and the nutritional benefits must be clearly demonstrable through evidence-based results. Increasing the coverage of micronutrients which can be biofortified, to include those such as folate, lysine and calcium, should also be a longer-term focus.

As with food fortification, investment is largely focused at the capital stage. Limited evidence makes it challenging to complete a total cost-benefit analysis. However, it is estimated that adaptive breeding (capital) costs for biofortification of total rice production in India would be approximately US$1,600,000 per year (Meenakshi et al. 2010). At the national level, this would be a relatively small investment. The largest beneficiaries of biofortification are likely to be low-income households, hence this cost should ideally be absorbed through private or public investment, rather than financed through farmer or consumer price increases. The potential economic benefits of such an investment are expected to be extremely high (Meenakshi et al. 2010), and delivered to demographics of low socioeconomic status.

4.2.3 Supplementation

Food processing and biofortification are complementary strategies to address MiND over near- to long-term timescales (>5-10 years). However, the social, health and economic costs of malnutrition in India are on-going, making urgent interventions – such as provision of dietary supplements - necessary to bridge this period. Dietary supplementation is most commonly delivered in tablet or powder-form.

The irreversibility and permanence of maternal and childhood malnutrition means that the most common target groups for dietary supplements are children, pregnant and lactating women (Stoltzfus 2011; Sachdev & Gera 2013). India has had national programmes delivering vitamin-A to children under the age of five (providing a biannual dosage), and a national anaemia control programme for pregnant women and children (delivering 100 tablets of iron and folic acid), for more than 30 years (Vijayaraghavan 2002). Evaluation of these programmes has indicated an extremely low success rate, attributed to economic, social and educational challenges. It's estimated that allocated funding for these programmes is sufficient to cover only 10% of requirements; less than 50% (vitamin-A) and 10% (iron) of necessary supplies are available; distribution is irregular, with <5% of pregnant women receiving more than 90 of the required 100-dosage; and due to poor nutritional education (Vijayaraghavan 2002), very poor compliance in intended beneficiaries.

India's large population size and prevalence of MiND makes the investment scale even more challenging. Supplementation can be inexpensive, with annual costs ranging from US$1-1.20 per person in South Asia and high benefit:cost ratios of (17:1) for vitamin-A supplements alone (The Micronutrient Initiative 2009). However it is, in relative terms, more expensive than interventions such as commercial food fortification and biofortification (in the order of dollars, rather than cents per person). We suggest that delivering the necessary investment and distribution networks for supplementation programmes in pregnant women and children should be an urgent and near-term priority. Additional key supplements should also be considered for these groups—lysine supplements for children, in particular. However, a long-term programme providing total coverage of the Indian population would be an unsustainable delivery model for addressing MiND. Total costs would be prohibitively high, and compliance would likely drop with time.

Supplementation should therefore form an urgent and short-term (<5 years) cornerstone in addressing MiND, but should be utilised as a bridge towards more efficient and sustainable delivery mechanisms such as fortification, biofortification, and dietary diversification. Thereafter, supplementation should be reserved for vulnerable demographics with significantly higher daily requirements, such as pregnant women—a practice also implemented in developed countries today.

5. Conclusion

In summary, our results have highlighted serious deficiency risks across most essential micronutrients in India. Scenario analysis suggests that current agricultural policies will be wholly insufficient in addressing micronutrient malnutrition— in fact, orientation towards maximising macronutrients (predominantly calories) may serve to exacerbate this issue. Broad-based interventions will remain an integral component in addressing MiND in India, with scenario analysis indicating significant potential in the reduction of supply chain losses, and increased dietary diversification through meat and dairy intake. However, India faces a significant challenge in simultaneously addressing macro- and micronutrient malnutrition with a growing population (for reference, rates of 50% MiND in 2030 would put more than 800 million at risk of deficiency in India alone). This limits its domestic potential to increase dietary diversification without causing a negative impact on caloric production.

We suggest that India must therefore address its MiND through an enhanced combination of intervention strategies, including dietary diversification (domestically and through increased imports), food processing and fortification, biofortification and supplementation. These interventions are best optimised using complementary approaches, geared towards specific demographics and evolving in line with India's changing socioeconomic and infrastructural development. The high benefit:cost ratios of the MiND intervention strategies considered here should make achieving this enhancement an urgent and sustained focus for the Indian government, and for international aid donors and policymakers.

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Part Two

The four chapters within Part One of this thesis provide insight into the scale, structure, and efficiency of our food systems. This provides a critical starting basis from which we can better understand the relative magnitude of inefficiencies across the value chain, identify hotspots, and the potential of interventions to target these.

From these analyses, two key areas emerged: the major global inequalities which exist in terms of food and nutritional production and access; and the dominant inefficiency of animal protein within the value chain. Solutions which seek to address malnutrition (in all its forms, including obesity and the rise of diet-related non-communicable diseases) and environmental sustainability should therefore have dietary equity and livestock products at their core.

Addressing these challenges will likely require an integration of solutions, including technological innovation, pricing, markets and trade, governance, and behaviour change. The three chapters included in Part Two explore a few of these areas.

The first of these seeks to quantify and understand the suitability of our current global and national dietary guidelines (which many may take as nutritionally complete, or even optimal). Whilst the sustainability challenge of our food systems is often considered to be a result of overconsumption, it has not yet been clear as to whether a global population following a recommended diet (without overconsumption) is environmentally sustainable. Chapter Five therefore attempts to quantify the greenhouse gas footprint of the WHO and national recommended diets to test their compatibility with our climate change targets.

Chapters Six and Seven focus on the potential impact of alternative high-quality protein sources. The first of these attempts to quantify the potential greenhouse gas emission savings and health benefits of meat-free substitutes (in this example, mycoprotein) across a range of price reduction scenarios. The final chapter aims to fill a major gap within the literature on the rapidly growing sector of aquaculture (i.e. fish farming). Global seafood production from aquaculture now exceeds that of traditional capture fisheries (Figure 1), and the majority of growth in seafood production is likely to come from fish farming in the coming decades. Despite the increasing influence of aquaculture in global protein production, no quantification of the sector's greenhouse gas emissions has been carried out to date. Aquaculture could hold significant potential in the production of high-quality, nutritious protein in a more sustainable way than terrestrial livestock, however the major research gaps in this area currently make such evaluations difficult. This work attempts to provide the first assessment of greenhouse gas emissions from global aquaculture (and potential future emissions scenarios) based on the best available data.

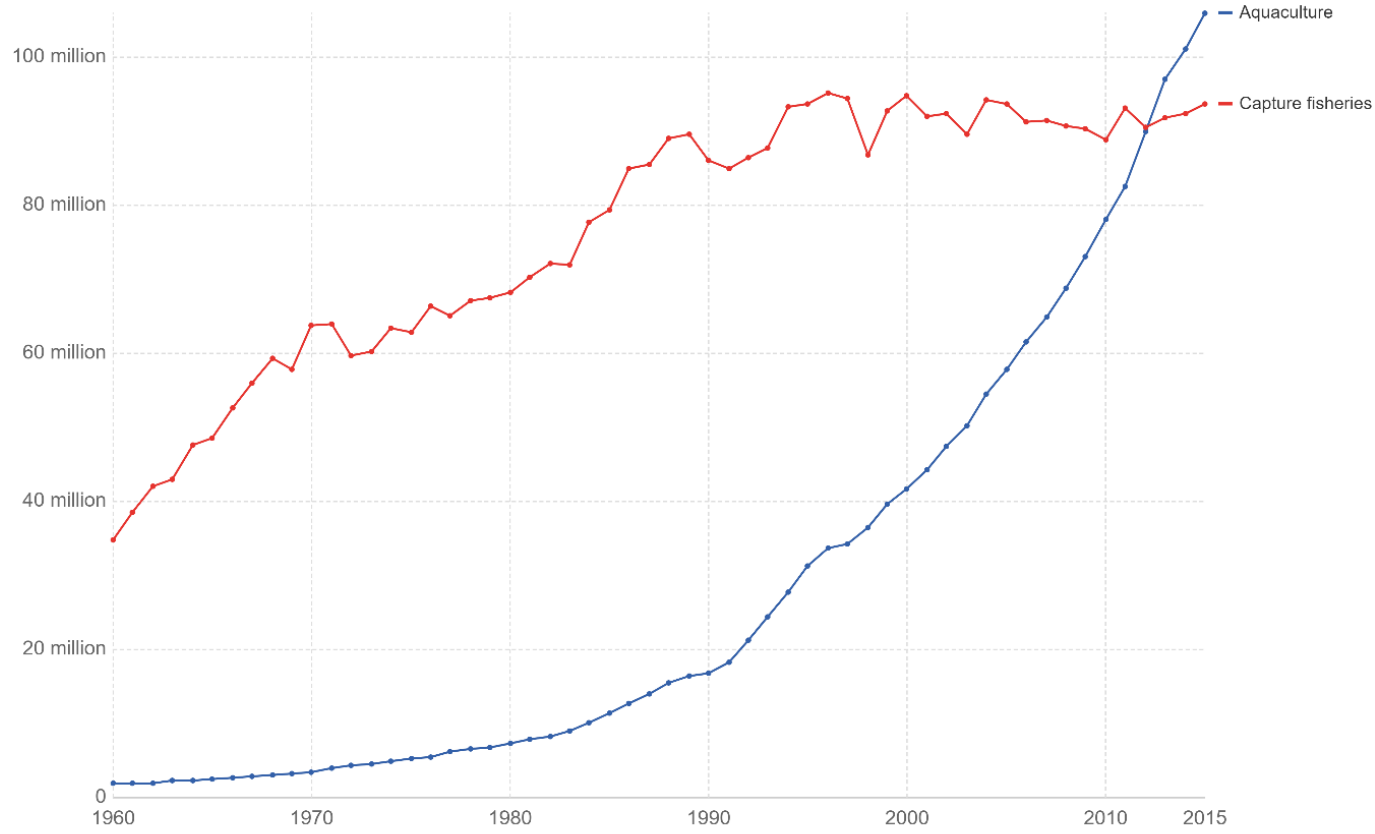

Figure 1: Global seafood production measured in tonnes per year from aquaculture (fish farming) and capture fisheries. Trends are derived from World Bank data (World Bank 2017).

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Chapter Five:
The impact of global dietary guidelines on climate change

After article: Ritchie, H., Reay, D. S., & Higgins, P. (2018). The impact of global dietary guidelines on climate change. *Global Environmental Change*, *49*, 46-55. doi: 10.1016/j.gloenvcha.2018.02.005

Abstract

The global food system faces an ambitious challenge in meeting nutritional demands whilst reducing sector greenhouse gas emissions. These challenges exemplify dietary inequalities—an issue countries have committed to ending in accord with the Sustainable Development Goals (by 2030). Achieving this will require a convergence of global diets towards healthy, sustainable guidelines. Here we have assessed the implications of dietary guidelines (the World Health Organization, USA, Australian, Canadian, German Chinese and Indian recommendations) on global greenhouse gas emissions. Our results show a wide disparity in the emissions intensity of recommended healthy diets, ranging from 687 kg of carbon dioxide equivalents (CO_2e) capita^{-1}yr^{-1} for the guideline Indian diet to the 1579 kgCO_2e capita^{-1}yr^{-1} in the USA. Most of this variability is introduced in recommended dairy intake. Global convergence towards the recommended USA or Australian diet would result in increased greenhouse gas emissions relative to the average business-as-usual diet in 2050. The majority of current national guidelines are highly inconsistent with a 1.5°C target, and incompatible with a 2°C budget unless other sectors reach almost total decarbonisation by 2050. Effective decarbonisation will require a major shift in not only dietary preferences, but also a reframing of the recommendations which underpin this transition.

1. Introduction

The global food system is currently failing to meet basic nutritional needs (Haddad et al. 2016), and is placing increasing pressure on planetary boundaries and resources (Alexander et al. 2016; Foley et al. 2011). Agriculture and food production systems are estimated to contribute more than one-quarter of global greenhouse gas (GHG) emissions (Edenhofer 2014; Tubiello et al. 2014)—a contribution which is projected to increase through population and economic pressures (Alexandratos & Bruinsma 2012). United Nations (UN) projections of global population growth to 9.8 billion by 2050 (United Nations: Department of Social and Economic Affairs 2017) will place increasing pressure on the intensification of agricultural systems. Economic growth is also expected to drive dietary change towards more GHG-intensive diets (Alexandratos & Bruinsma 2012). Business-as-usual (BAU) pathways are not only expected to exceed global climate targets for 2°C scenarios (Wellesley et al. 2015), but will also place unsustainable resource pressures on land (Alexander et al. 2016; Wirsenius et al. 2010), freshwater supplies (Mekonnen & Hoekstra 2016), and marine resources.

Despite continued improvements in agricultural output (Foley et al. 2011), poor nutritional health remains a widespread, and in some cases, a growing issue (FAO et al. 2015). More than 800 million people are defined as undernourished, an estimated two billion suffer from micronutrient deficiencies, and 40 percent of adults globally are classified as overweight or obese (with increasing links to the incidence of non-communicable diseases—NCDs—such as cancer, stroke and heart disease)(FAO 2017b). This 'triple burden' of malnutrition is reflective of the large dietary inequalities which exist both between and within countries.

To simultaneously meet the 2nd and 13th Sustainable Development Goals (SDGs), of ending malnutrition, and combating climate change (United Nations 2016) (in addition to meeting the international climate change mitigation target of 2°C (Wollenberg et al. 2016)), a convergence of global diets towards more healthy and sustainable patterns is of pressing importance. The average diet across most high-income countries (FAO) is well in excess of WHO recommendations for caloric, meat and sugar consumption, with increased risk of NCDs and obesity (WHO 2015). Conversely, the typical diet across many low and middle-income nations (FAO) falls below quantity, quality and diversity requirements—increased intake of commodities such as meat, dairy, and fish are likely to improve health and social outcomes (FAO 2011; Rivera et al. 2003; Zotor et al. 2015). Agricultural production is also likely to become increasingly important for countries in meeting their climate change mitigation commitments (Elbehri, A. et al. 2017; The World Bank 2017)—a constructive means of defining and monitoring demand-side progress in the food sector will be essential for this. Convergence of national dietary patterns towards a healthy global recommended level may contribute to a significant reduction in the GHG emissions intensity and NCD risks of average high-income diets, and a healthy, sustainable improvement in low-income diets.

There are currently no internationally agreed guidelines for what a simultaneously nutritious and environmentally sustainable mainstream human diet constitutes. A number of studies have shown that a transition towards pescetarian, vegetarian or vegan diets would result in significant GHG savings relative to meat-intensive diets (Tilman & Clark 2014; Springmann, Godfray, et al. 2016; Van Dooren et al. 2014; Scarborough et al. 2014). While the incidence of vegetarianism has shown some increase in developed economies (Beverland 2014), the adoption of more flexitarian or meat-reduction based dietary transitions have shown greater uptake and social acceptance (Dagevos & Voordouw 2013; De Boer et al. 2014). Convergence guidelines which recommend a reduction rather than elimination approach to meat may therefore be more effective in increasing dietary transition rates. Convergence towards a moderate mixed diet—rather than wholly plant-based diets—may also be important in balancing environmental concerns with health outcomes in low-income nations (where dietary diversity is often poor, and high-quality alternative protein products are often unavailable or expensive). Relative to sustainability-focussed dietary advice, dietary health guidelines are better-established, with WHO global-level recommendations (WHO 2015), and national-level nutritional plans in more than 100 countries (Fischer & Garnett 2016). Despite international guidelines, significant variations in national recommendations remain (ibid).

Here, for the first time, we have attempted to assess the degree to which convergence of global average diets to a defined set of guideline levels could simultaneously achieve improved human health and significant reductions in GHG emissions from global agriculture. This analysis comprised several steps. First, all available country-level dietary guidelines (FAO 2017a) were reviewed to assess their clarity in providing clear, quantitative recommendations for an average healthy diet. Next, a range of representative national dietary guidelines were assessed for their resultant per capita GHG emissions using commodity-specific GHG-intensities derived through life-cycle (LCA) meta-analyses (Tilman

& Clark 2014). National guidelines—including the USA, China, Germany, Australia, Canada and India—were compared relative to income-dependent dietary projections (Tilman & Clark 2014) and WHO healthy diet guidelines (WHO 2015). This analysis revealed wide disparity in the GHG-intensity of national recommended diets—with some showing a minimal reduction in GHG emissions relative to the average projected income-dependent diet in 2050. Global agricultural GHG emission pathways were then assessed based on the assumption that average diets converged on each of these global or national recommendations by 2050—such a convergence would allow for both nutritional and GHG mitigation targets to be addressed simultaneously.

Finally, we assessed the compatibility of current dietary trends with national and WHO guidelines, and the likelihood of their convergence in the near (2030, the end date of the SDGs) and longer (2050) term. Annual rates of change in food consumption were estimated for three exemplar countries which together cover a full range of dietary compositions—the USA, China and India—based on extrapolation from current FAO consumption figures for the period 2000-2013 (the latest full dataset available). (FAO). This provides some indication of the magnitude of change in dietary patterns necessary for these and similar nations to meet dietary guidelines relative to current trends.

A number of publications have assessed the GHG intensity of dietary choices, as well as the reduction potential of dietary changes. Several such studies have looked at the global comparison between business-as-usual (or income-dependent) projected diets towards 2030 and 2050 alongside the World Health Organization (WHO) healthy diet guidelines (Tilman & Clark 2014; Springmann, Godfray, et al. 2016). These studies attempt to address the diet-sustainability-health trilemma through GHG and health benefit quantification. Other analyses have looked more regionally or nationally at the potential mitigation impact of dietary change—either in terms of meat reduction, substitution, or adoption of Mediterranean, vegetarian or vegan diets (Berners-lee et al. 2012; Westhoek et al. 2014; Stehfest et al. 2013; Scarborough et al. 2014). It is well-established within the literature that an overall reduction in meat (particularly red meat) products is synonymous with GHG reduction and health benefits.

However, no analysis to date has attempted to quantify the suitability or impact of adoption of current national dietary guidelines with respect to climate mitigation, and the more recently established SDG targets. Fischer & Garnett (2016), of the UN FAO, to our knowledge have produced the only large-scale assessment of sustainability within national dietary guidelines. However, this work, does not attempt any quantification of impacts of guideline adoption and instead focuses on a qualitative assessment of which countries have made reference to sustainability within their recommendations.

Our work therefore attempts to provide the first comparison of national dietary guidelines in terms of GHG emissions. This was carried out through the adoption of similar methods utilised in global-level assessments of diet-environment-health links by Tilman & Clark (2014) and Springmann et al. (2016), but applied within the context of national-level recommendations. Assessment of the relative impact of countries switching from their current average diet to nationally recommended intake across greenhouse gas, eutrophication and land use metrics has been previously assessed, with a focus on the impact of this transition rather than the comparison of national recommended diets or their compatibility with climate targets (Behrens et al. 2017).

2. Methods

National food-based dietary guidelines were reviewed based on those publicly available in FAO repositories. These cover 86 countries across all regions, with countries at all stages of development. A qualitative assessment of the suitability of national guidelines for sustainability has been previously published by the FAO (Fischer & Garnett 2016). We attempt to build upon this work through a quantitative assessment of the compatibility of these guidelines with climate targets.

2.1 Quantifying emission footprints of recommended diets

The average diets of six national guidelines—India, China, Germany, Canada, Australia and the USA, in addition to the WHO healthy (WHO 2015) and income-dependent 2050 diet (Tilman & Clark 2014)—were quantified in terms of annual GHG emissions per capita based on commodity-specific life-cycle analysis (LCA) meta-analyses carried out by Tilman & Clark (2014). This meta-analysis reviewed 555 LCAs across 82 food items. These LCAs were sourced based on a criteria of complete 'cradle to farmgate' boundary scope, including emissions from pre-farm activities such as fertilizer, feed production and infrastructure construction. This footprint does not include post-farmgate activities such as transport, processing and consumer use. For reference, analysis suggests that this post-farmgate component of the overall footprint would approximately add a further 20% to total emissions (Weber & Matthews 2008; Tilman & Clark 2014). Due to the large uncertainties involved in calculating levels of land-use change (LUC), and the resultant GHG emissions, LUC has also not been included. This study therefore focuses only on emissions related to agricultural production.

Tilman & Clark (2014) derived their income-dependent 2050 diet based on eight economic groups – six groupings plus China and India independently (aggregated based on per capita gross domestic product; GDP); GDP-consumption relationships and modelled using the Gompertz 4p curve function. The income-dependent diet differs from recommended diets in terms of its total caloric content. Despite small variability in the energy composition of the average recommended diet between national and WHO guidelines, all fall within the range of 2000 to 2500 kcal $person^{-1}$ day^{-1}. Since the income-dependent diet is based on projected food demand rather than healthy, recommended intakes, average caloric supply across economic groups is notably higher (ranging from 2250 kcal in the lowest economic group to 3590 kcal $person^{-1}$ day^{-1} in the highest). Whilst this represents a large difference in caloric intake between the income-dependent and recommended diet scenarios, this gap provides an important indication of the level of dietary change required by 2050 to reduce average levels of consumption to match healthy dietary guidelines. The impact this has on resultant GHG-intensity of diets also provides an important comparison—the impact of caloric overconsumption relative to recommended consumption. We have therefore not adjusted the income-dependent diet to attempt to reach parity in caloric intake.

Average diets were quantified in terms of ($gday^{-1}$, and subsequent $kgyear^{-1}$) across nine key food groups: staples, pulses, sugar, oils, fruit and vegetables, dairy, fish, poultry and red meat. Due to the nuances of dietary preferences both within and between countries, a finer-resolution breakdown of guidelines beyond these nine categorisations is not possible. Food consumption (in $gday^{-1}$) across each of these food categories for each of the analysed diets are provided in Supplementary Table 1.

Whilst national dietary guidelines are based on recommendations of actual consumption (i.e. the quantity finally eaten), Tilman & Clark's 2050 income-dependent diet is based on final household food *demand* which refers to the quantity eaten, plus the amount wasted at the consumption level. The predominant aim of our analysis is to illustrate the differences in national guidelines – not the impact of actual waste and consumption patterns across the world. Including emissions related to food wastage may hide the key conclusions in relation to the suitability and comparability of national guidelines. In our results we therefore present the breakdown of emissions related to dietary guideline intakes (in the absence of waste), but additionally show the impact that correction for household waste would have on final emissions. This latter correction allows for direct comparison with the 2050 income-dependent diet.

Our adjustments for food wastage at the household level are based on the 'consumption' percentage figures published by the FAO (Gustavsson, J. et al. 2011). These estimate the percentage losses at each stage of the supply chain by commodity group (e.g. meat, milk, cereals) by region. For national guidelines, our waste figures reflect the regional figures of the given country (for example, North American figures have been used for the USA and Canada). Global average percentage figures have been used for the WHO Healthy Diet scenario.

The terminology of dietary guidelines can vary, especially between approaches for different food groups. For food groups, such as staples, where a range of values (in grams per day) is given, we have assumed the median intake of this range. Guidelines for dairy, fish, fruit and vegetables tend to work on a minimum basis (e.g. "consume at least 1 portion of dairy per day"); for these groups we have assumed consumption meets (but does not exceed) this recommendation. Guidelines for meat, oils and sugars tend to work on a maximum 'recommended' limit (i.e. limit sugar consumption to 25 grams per day). For these food groups we have assumed that—since current intake in many high-income countries tends to greatly exceed these maximum guidelines—people would consume up to (but not exceed) this upper threshold.

Per capita dietary emissions were calculated using average emission factors (EFs) derived based the LCA meta-analyses explained above. The EFs applied in this study are detailed in Supplementary Table 3. Dietary guidelines are typically defined based on recommended levels of total red meat consumption—this incorporates bovine, pig, and mutton meat, for which there are significant differences in EFs. To account for this, we have assumed a dietary consumption ratio between red meat products in line with 2013 global FAO production figures—58% of red meat production was in the form of pigmeat (108Mt), 35% bovine (66Mt), and 7% mutton meat (13Mt)(FAO n.d.). EFs for red meat consumption have therefore been weighted based on this ratio of consumption. An obvious limitation of this methodology therefore lies in its assumption that future red meat consumption preferences are in line with current trends.

This analysis is primarily focused on demand-side (rather than supply-side) mitigation. The EFs applied in this study make no assumptions on changes in the GHG-intensity of production. Our income-dependent and WHO healthy diet results are therefore closely in line with the results of Tilman & Clark (Tilman & Clark 2014). *Springmann et al. (2016)*, who assess the impact of constant reductions in GHG-intensity through to 2050 on the footprint of WHO, Mediterranean, vegetarian and vegan dietary preferences (Springmann, Godfray, et al. 2016), therefore present slightly different results. Fish and other seafood is also excluded from *Springmann et al. (2016)'s* analysis.

2.2 Quantifying global agricultural emissions by national diet adoption

Scenarios of total global agricultural emissions through dietary convergence were mapped based on calculated dietary per capita footprints, and UN population projections (United Nations: Department of Social and Economic Affairs 2017) from 2013 to 2050. These scenarios were mapped based on the assumption that the global average diet would converge on each respective dietary guideline. The nutritional requirements of individuals depends on a range of factors including age, gender, physiology and activity levels—in this analysis we assume that the distribution of intakes around the average dietary intake follows an approximate log-normal distribution.

To account for the impact of food wastage in the household (i.e. corrected for food demand rather than direct consumption), we assume that under each dietary guideline scenario the commodity-specific household wastage percentage figures are the same, based on global average FAO figures (Gustavsson, J. et al. 2011). Our results present these pathways both with and without correction for food wastage to show this impact. We assume food wastage percentage figures remain constant throughout the assessed period (although future modelling of the impact of food waste scenarios would be a useful addition).

2.3 Assessing pathways for convergence on recommended diets

In comparing required transition pathways which would be necessary to converge national consumption patterns on WHO or national dietary guidelines by 2030 or 2050, current (2013) and recent trends in red meat, poultry and dairy consumption were assessed in the USA, China and India using FAO Food Balance Sheet (FBS) data. Current consumption profiles were mapped from 2013 average per capita levels, with an annual change in intake defined based on the historic annual rates of change from 2000-2013. These profiles map the dietary pathways which would result if this rate of change was maintained through to 2030/50. Convergence pathways for WHO and national guidelines were mapped based the annual rate of change needed to meet recommendations by 2030/50 from 2013 consumption levels. This analysis can be easily replicated at any level and for any country to assess the level of dietary shift which would be required to reach healthy and sustainable dietary intakes, and could be further utilised as an approach for tracking progress in this transition.

Since FAO FBS data is based on food demand (which equates to food intake plus consumption waste), WHO and national guidelines have been adapted to reflect regional household waste percentage figures by commodity as derived from Gustavsson et al. (2011).

2.4 Study limitations

This study aims to assess the food-based GHG-intensity and sectoral emissions which would result from the adherence of average diets to a range of global and national dietary guidelines. This has the obvious limitation in its assumption that such dietary advice would be followed. As evidenced in our results, actual consumption trends in many countries lie far from recommended values. For this reason, we have provided some examples of dietary transition requirements to meet these guidelines by 2030/50.

In the calculation of dietary GHG-intensity, we have applied EFs based on global average commodity-specific LCA figures. Actual emissions-intensity of agricultural production will have significant regional variations—appropriate weighting of these values would strongly depend on future global trade scenarios which have not been accounted for in this analysis.

The LCAs included in this study, as explained, have been defined based on a 'cradle-to-farmgate' scope, which excluded post-farmgate and land-use change emissions. Depending on future trade and land-use scenarios, emissions from these components (LUC, in particular) could form a significant portion of this sector's emissions. The measurement of emissions from agricultural production alone does not therefore capture the full impact of the global food system. It does, however, incorporate CO_2 and the majority of non-CO_2 (methane and nitrous oxide) emissions, which typically dominate the sector's total GHG impact. The EFs related to such LCAs will likely change over time if progress is made on SDG7 of transitioning towards lower-carbon energy sources; decarbonisation of the energy and transport sectors would reduce the GHG-intensity of some components of LCAs including agricultural inputs, on-farm machinery and transport.

3. Results

3.1 Global and national dietary guidelines

We reviewed the 86 countries which have published food-based dietary guidelines within the FAO repository (FAO 2017a). While most national guidelines are based around the general recommendations published by the WHO (WHO 2015), there are notable differences between countries, not only with respect to advised dietary patterns, but also in terms of clarity, comprehensibility and quantification. Since national guidelines are typically adapted to the nutritional status, eating habits and food availability of a given country, some variation in the average recommended diet is to be expected. However, many national guidelines appear to lack the level of quantitative detail or guidance necessary for stakeholders (e.g. health workers and members of the public) to clearly know and understand the need for the levels of intake they should be targeting. In Supplementary Table 2 we provide the breakdown of recommendations in grams per person per day across the nine commodity groups for a range of countries where national guidelines are insufficient. These data highlight for which commodities guidance is clear, and others where it is not quantifiable. For example, the UK guidelines clearly recommend consumption of “at least five portions of fruit and vegetables per day” (which provides a quantifiable amount), but states only to “eat less red and processed meat” (which provides no quantifiable guidance on safe or healthy intake).

To assess country-to-country variations in terms of GHG-intensity of the average recommended diet, we quantified the footprint of six national guidelines which cover a range of dietary patterns—USA, Canada, Australia, Germany, China and India. This covers the spectrum from typically higher GHG-intensity nations (USA, Canada, and Australia), to one of the lowest expected dietary GHG footprints—India. Germany has been included as one of only four countries identified by the FAO as overtly including environmental considerations (which are typically oriented towards climate change impacts) within its dietary recommendations (Fischer & Garnett 2016).

The estimated per capita annual GHG footprints of nationally recommended diets are shown in Figure 1, presented alongside the WHO’s healthy diet guidelines (WHO 2015), and global average income-dependent diet in 2050. The income-dependent diet was based on projected regional economic growth trends and its relationship to dietary transitions (both in quantity and composition).

Climate change mitigation targets and indicators as established within the SDG framework reflect those agreed upon within the United Nations Framework on Climate Change (UNFCCC) and 2015 Paris Agreement (United Nations 2017). Within the Paris Agreement, UN parties have committed to “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (UNFCCC 2015). To meet a global target of 2°C under median emissions pathways would require a reduction of GHG emissions to 23 $GtCO_2e$ per year in 2050 (Climate Action Tracker 2017). To maintain a 66% chance of keeping temperatures below 1.5°C, annual emissions are likely to have to reduce to 13 $GtCO_2e$ per year by 2050. Currently the sum of proposed national targets (Nationally

Determined Contributions; NDCs)—if fulfilled—are estimated to take us well beyond both targets to a median temperature rise of 3.2°C (Climate Action Tracker 2017).

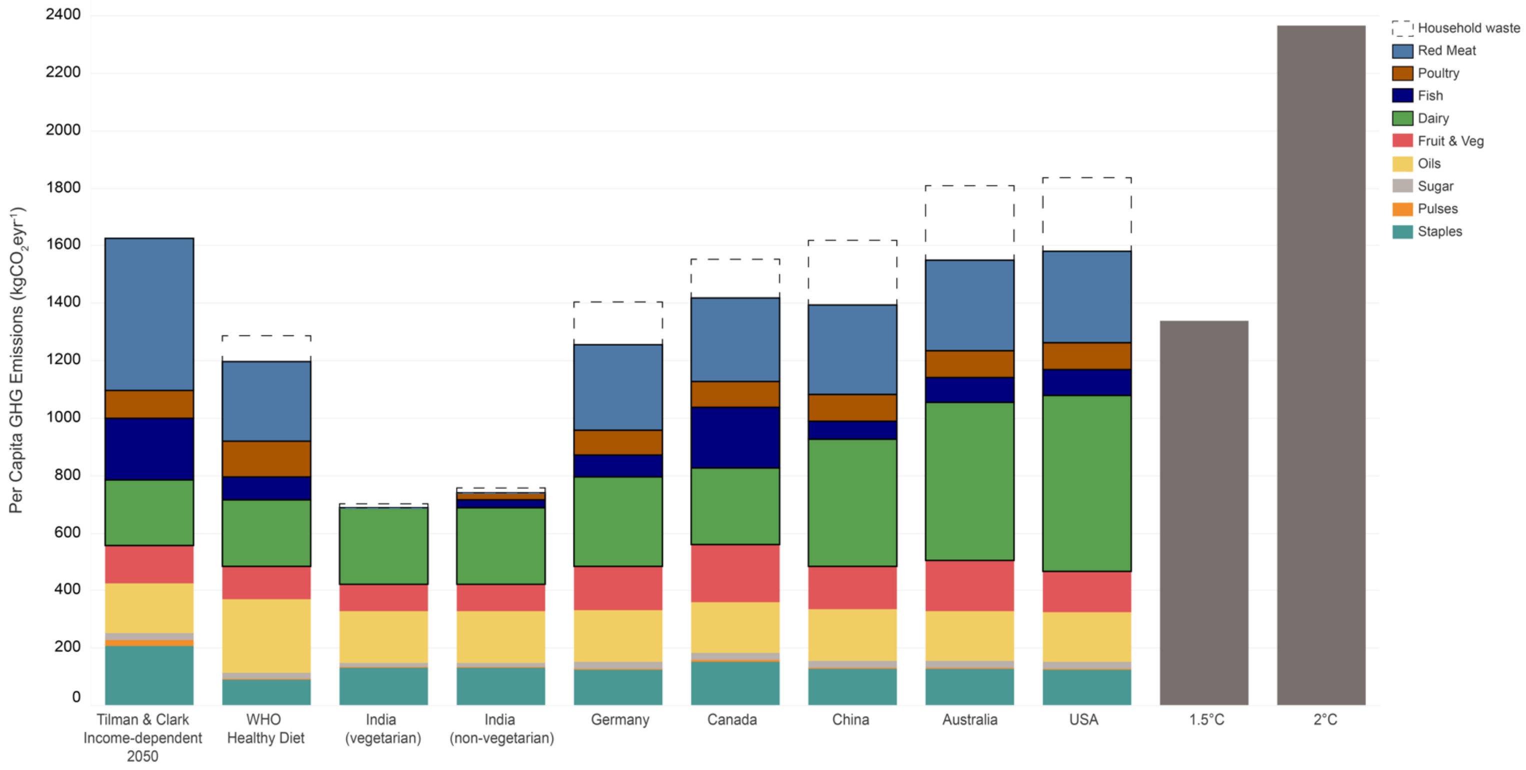

Figure 1: Per capita greenhouse gas emissions across income-dependent, WHO and national dietary guidelines. Annual breakdown of per capita food production (cradle-to-farmgate) emissions across the average income-dependent diet in 2050, WHO healthy diet, and national dietary guidelines by commodity group. Dashed lines are used to represent the additional GHG emissions resultant from food wasted at the household level, where the income-dependent diet has already been corrected to food demand (rather than intake). Animal-based products have been highlighted by black outline shading. Also shown are the average per capita GHG emissions (across all sectors) for 1.5°C and 2°C pathways.

Sectoral breakdown of how current NDCs will be increased at global or national levels to meet these targets is currently not clear. However, it's clear that business-as-usual (BAU) projected emissions from agricultural production are incompatible with the level of reduction needed to keep temperatures below 1.5°C or 2°C. Published estimates of BAU emissions from agriculture range from 15.5 to 20 $GtCO_2e$ in 2050 (Tilman & Clark 2014; Wellesley et al. 2015)—either exceeding the total global budget for 1.5°C or consuming the majority (67-87%) of a 2°C budget of 23 $GtCO_2e$. This lack of determination of necessary GHG emissions reductions (on a total or per capita basis) makes it challenging to benchmark food-specific reduction scenarios relative to targets within the Paris Agreement (or the SDGs, by default) since its required contribution is dependent on mitigation progress within other sectors. However, here we benchmark per capita dietary food footprints relative to total economy-wide average per capita emissions in 2050 to meet a 2°C budget of 23 $GtCO_2e$ (2365 $kgCO_2e$ $capita^{-1}yr^{-1}$) or a 1.5°C budget of 13 $GtCO_2e$ (1337 $kgCO_2e$ $capita^{-1}yr^{-1}$).

Our results, shown as the average per capita food-related GHG emissions resultant from income-dependent, WHO healthy diet and national dietary guidelines are seen in Figure 1. These figures are also summarised in Table 1, with and without adjustment for household-level waste. In line with previous studies (Tilman & Clark 2014; Springmann, Godfray, et al. 2016), our results indicate that a transition from the average income-dependent diet in 2050 to the WHO's global recommended healthy diet would reduce per capita dietary GHG emissions. At the national level, there is significant variability between dietary GHG intensities; this range extends from the recommended vegetarian Indian diet (at 687 $kgCO_2e$ $capita^{-1}yr^{-1}$) to the USA diet guidelines (at 1579 $kgCO_2e$ $capita^{-1}yr^{-1}$). Once food wastage estimates are included, this difference increases to 702 $kgCO_2e$ $capita^{-1}yr^{-1}$ in India, relative to 1837 $kgCO_2e$ $capita^{-1}yr^{-1}$ in the USA.

Dietary scenario	**Per capita GHG emissions (prior to correct for household waste) ($kgCO_2e$ $capita^{-1}yr^{-1}$)**	**Per capita GHG emissions (including household waste) ($kgCO_2e$ $capita^{-1}yr^{-1}$)**
Income-dependent 2050 diet	-	1626
WHO Healthy Diet	1197	1288
India (vegetarian)	687	702
India (non-vegetarian)	740	757
Germany	1256	1403
Canada	1395	1620
China	1419	1552
Australia	1551	1807
USA	1579	1837

Table 1: Per capita greenhouse gas emissions across income-dependent, WHO and national dietary guidelines. Annual per capita food production (cradle-to-farmgate) emissions across the average income-dependent diet in 2050, WHO healthy diet, and national dietary guidelines by commodity group. Figures are provided as those with and without correction for regional household-level waste estimates. Tilman & Clark's (2014) 2050 income-dependent diet is based on food 'demand' rather than 'intake' and therefore already includes food wastage estimates.

Our results (Figure 1) demonstrate the need for dietary transition when compared to average per capita GHG budgets for 1.5°C or 2°C in 2050. With the exception of the recommended Indian diets, the average dietary footprint exceeds the total per capita 1.5°C budget under all national dietary scenarios, as indicated by the grey bar in Figure 1 which includes per capita GHG emissions from all sources. The WHO Healthy diet falls slightly below the 1.5°C budget, but would require almost total decarbonisation from all other sectors – relying on attainment of other SDGs, including SDG7 for which progress is tracked based on the share of renewables in the energy mix. All dietary footprints fall within the per capita budget of the average 2365 $kgCO_2e$ $capita^{-1}yr^{-1}$ budget for 2°C, however most of this budget would be consumed by agricultural production leaving little room for other sectors including energy and transport.

In Figure 1, animal-based commodities are highlighted by a black outline around the upper part of each bar. Note that while there is some degree of variation in the GHG-intensity of the plant-based component of the modelled diets, this deviation is typically small (ranging from 421$kgCO_2e$ to 560 $kgCO_2e$ $capita^{-1}yr^{-1}$). This is true across income-dependent, WHO and nationally recommended diets. The inter-dietary variability in GHG footprint is primarily introduced in the consumption of animal-based products. This ranges from 266 $kgCO_2e$ to 1112 $kgCO_2e$ $capita^{-1}yr^{-1}$, a four- to five-fold difference. We may therefore approximate that the global average per capita GHG emissions associated with the plant-based component of both dietary trends and recommendations account for 490±70 $kgCO_2e$ yr^{-1}, with the remaining variability introduced through the consumption of animal-based products.

Of note in this analysis is the relatively low GHG emissions footprint of recommended diets in India – stemming from the unique nature of India's guidelines. Most nations detail meat and fish products as a core pillar of their dietary guides, with a smaller subset of countries providing an optional substitution of pulses. This is an important distinction compared to Indian recommendations, which are predominantly vegetarian; here, a side-note is provided for non-vegetarians to replace one portion of pulses daily with either meat, fish or egg. As a result, even its non-vegetarian recommended diet has a comparably low carbon footprint. India's recommended diet has an almost identical GHG-intensity to vegetarian diets analysed in previous studies (at 650-700 $kgCO_2e$ $capita^{-1}yr^{-1}$) (Tilman & Clark 2014; Springmann, Godfray, et al. 2016).

In contrast, the currently recommended diet in the USA has a high GHG emissions footprint, being of the same magnitude as that of the income-dependent diet in 2050 prior to adjustment for wastage. With correction for household food wastage – which is significant in high-income countries – emissions exceed that of the income-dependent diet by greater than 200 $kgCO_2e$ $capita^{-1}yr^{-1}$. Australian guidelines produce a similar result. Food sustainability issues, especially within such higher-income nations, are often discussed in relation to dietary overconsumption (Blair & Sobal 2006). However, while excess consumption undoubtedly adds to resource pressures, our results suggest that the GHG-intensity of the average USA diet would still be very high even were it to converge with national nutritional guidelines (which are not excessive in caloric terms, suggesting dietary composition is more important than total energy intake). This means our evaluations of future income-dependent dietary pathways need to assess both dietary composition and excessive intake as sources of GHG emissions (and potential mitigation areas). As shown in Figure 1, the largest GHG contributor to this footprint is its recommendation of three dairy portions per day. This is three times that recommended in the WHO healthy diet, while the USA's guidelines on other animal-based components - red meat, poultry and fish - are closely in line with WHO recommendations.

The recommended intake of dairy products is a key differentiator across all modelled diets. This is in contrast to red meat, poultry and fish guidelines which (with the exception of India) typically reflect WHO advice. The upper limits on recommended meat intake result from the strong relationships between excessive red meat consumption and risk of Non-Communicable Diseases (NCDs), including heart disease, stroke and cancer (Chen et al. 2013; Micha et al. 2010; Lozano et al. 2012). In contrast, milk and dairy intake has been typically discussed in global nutritional guidance in terms of under-consumption and calcium deficiency (Legius et al. 1989; Kumssa et al. 2015). Therefore, while upper limits are often defined for meat (especially red and processed meat), recommendations for dairy products are based on minimum thresholds. This may be a sensible approach for health guidelines, however the lack of commonality on recommended dairy intakes (and the impact this has on GHG emissions) suggests that a redefinition of advice which meets climate change mitigation objectives as well as those for health could be important.

3.2 Converging global diets for health and sustainability guidelines

If we are simultaneously to address SDG2 in ending all forms of malnutrition (including undernutrition, micronutrient deficiencies, and overconsumption), and SDG13 of mitigating climate change, a convergence of global diets towards a healthy, low carbon confluence will be necessary. To assess the level of GHG emissions which would result from global convergence to each of the recommended diets through 2030 to 2050, we have combined average per capita footprints shown in Figure 1, with UN population projections (United Nations: Department of Social and Economic Affairs 2017). These global emissions convergence scenarios from 2009 to 2050 are presented in Figure 2. These assume household food wastage percentages in line with global average figures to allow for comparability with the income-dependent 2050 scenario, which is given as food demand rather than intake. We provide these figures both prior to and after correction for household waste for comparison in our Supplementary Data.

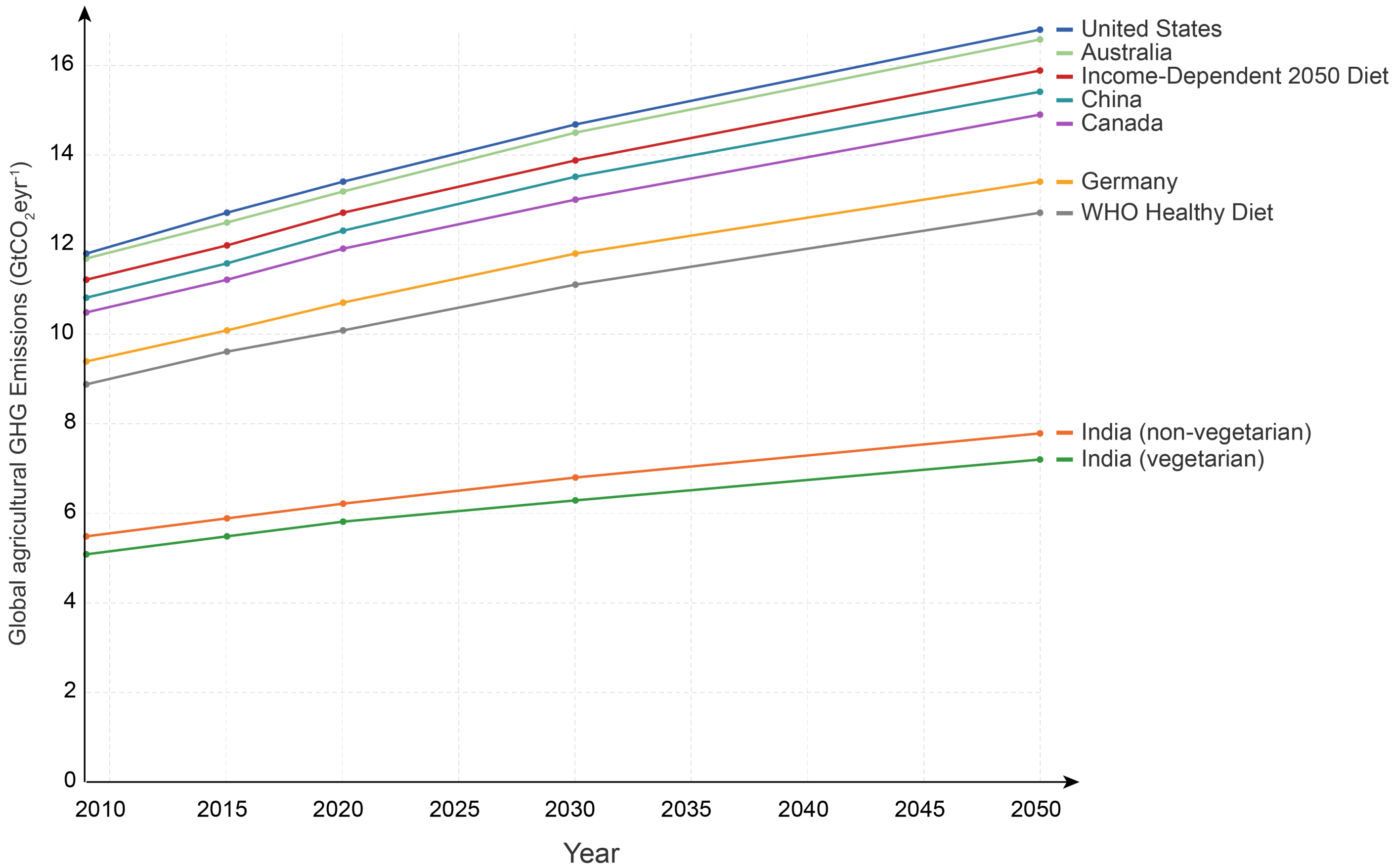

Figure 2: Global greenhouse gas emissions from food production if the global population adopted the average income-dependent, WHO healthy or national recommended diets. Global greenhouse gas emissions from 2009-2050 if global diets converged on the WHO healthy or national recommended diets of exemplar countries, in comparison to the projected average income-dependent diet in 2050.

As shown, business-as-usual income-dependent consumption would result in the highest level of global emissions, at 15.5-16 $GtCO_2e\ yr^{-1}$. Our results are in line with published estimates from Tilman & Clark (2014) of between 15-16 $GtCO_2eyr^{-1}$ in 2050. Convergence towards the WHO healthy diet would result in significant GHG reductions, reducing emissions in 2050 by approximately 4 $GtCO_2e\ yr^{-1}$ relative to the income-dependent scenario. As expected from per capita GHG footprint results, global emissions deriving from convergence on each of the national recommended diets vary significantly. Maximum GHG reductions in the agriculture sector would be realised if global diets were to converge towards Indian recommendations (totalling only 6.7 $GtCO_2e\ yr^{-1}$). The Indian diet recommendations strongly match the modelled results by Tilman & Clark (2014) of adoption of a vegetarian diet; they estimate global emissions of 6.5 $GtCO_2e\ yr^{-1}$ with global adoption of this diet. The large differentiation between the emissions intensity of a vegetarian-oriented

Indian diet and higher meat iterations in income-dependent and national guidelines reiterates previous results which show large differences between meat-eater, Mediterranean, vegetarian and vegan diets (Berners-lee et al. 2012; Scarborough et al. 2014; Van Dooren et al. 2014; Westhoek et al. 2014).

With the exception of India, GHG emissions from each of the national guidelines examined here exceed the WHO healthy diet. If global diets were to converge on the recommended USA or Australian diet, emissions would exceed that of a business-as-usual (income-dependent) pathway when allowing for household wastage. Canadian guidelines would result in almost no emission savings relative to the income-dependent scenario. This result further suggests that dietary guidelines for these nations in particular—despite meeting health criteria—are wholly inadequate in terms of addressing climate change.

Our analysis has focused on demand-side impacts on production-phase GHG emissions only. These results may therefore be considered upper estimates of emissions in each scenario, assuming that supply-side measures will further reduce the GHG emissions intensity of global food production in the future. To contextualise supply-side mitigation potential, estimates suggest that a halving of food losses and waste could result in global reductions up to 1.8 $GtCO_2e\ yr^{-1}$ (Tilman & Clark 2014); and improved livestock management in the form of enhanced feed digestibility, use of feed additives, animal and manure management could mitigate a further 1.2 $GtCO_2e\ yr^{-1}$ (totalling 3 $GtCO_2e\ yr^{-1}$) (Herrero et al. 2016).

3.3 National requirements for convergent pathways

While discussion of the suitability of national guidelines and exploration of dietary convergence points is timely, it is important to note that current (and projected) food consumption patterns lie far from both WHO and national recommendations (Alexandratos & Bruinsma 2012). Global inequalities in food intake mean that both under- and overconsumption with respect to guideline averages is widespread.

To assess how rates of dietary transition across nations would have to change in order to reach WHO or national guidelines, we have mapped the convergence pathways of the USA, China and India, and compared these to recent (2000-2013) trends in average consumption.

Defining a target convergence date by nation is difficult as no overt targets of this type have been set by governments. Here we have mapped pathways based on convergence by 2030 (the end date of the SDGs), and 2050 (likely to be deemed as more realistic given the scale of change necessary). Our analysis indicates that the major variability in dietary climate impact lies in the consumption of animal-based products; we have therefore focused on potential pathways in red meat, poultry and dairy consumption. Actual national trends (as opposed to convergence scenarios) have been extrapolated from 2013 per capita commodity-specific supply data as provided in the FAO's Food Balance Sheet (FBS) (FAO). Current rates of transition are here defined as the annual average change (in kilograms per capita) from 2000-2013 reported for each nation.

Table 2 presents results for the USA, China and India, summarising current food supply, WHO and national guideline figures and the annual rates of change needed to reach these guidelines by 2030 or 2050, assuming linear change. Actual rates of change are also shown for context.

In the United States, the reduction pathways which would be necessary for convergence towards the WHO and USA recommended diet are closely matched for red meat and poultry intake. In the case of red meat, average per capita demand would have to consistently decrease by 3 $kgyr^{-1}$ to converge with current guidelines by 2030, or 1.4 $kgyr^{-1}$ by 2050. Average per capita demand for red meat in the USA has been declining since 2000, but at a much slower rate (0.3 $kgyr^{-1}$). A more than ten-fold increase in reduction rates would therefore be necessary to reach the guideline levels by 2030, or a five-fold acceleration by 2050. In contrast to red meat consumption, poultry demand has been slowly increasing over the last decade (at an average rate of 0.2 $kgyr^{-1}$). This highlights a potential trade-off in dietary transition: the substitution of red meat with poultry is often recommended for both ecological and health reasons (Springmann, Mason-D'Croz, et al. 2016), however, to converge on a healthy and sustainable diet, *total* average meat consumption must be decreased in such nations. To maximise GHG mitigation and health impacts, the pathways of high meat-consuming nations may therefore follow a two-stage reduction process, firstly with a substitution of poultry for red meat (which will temporarily increase poultry consumption), before a subsequent reduction in poultry also.

	Food supply 2013 (kgyr⁻¹)	WHO guideline (kgyr⁻¹)	National guideline (kgyr⁻¹)	Current consumption trend (kgyr⁻¹)	Annual change to WHO guideline by 2030 (kgyr⁻¹)	Annual change to national guideline by 2030 (kgyr⁻¹)	Annual change to WHO guideline by 2050 (kgyr⁻¹)	Annual change to national guideline by 2050 (kgyr⁻¹)
USA (Red Meat)	64.3	13.4	15.3	-0.3	-3.0	-2.9	-1.4	-1.3
China (Red Meat)	36	13	13.8	-0.01	-1.4	-1.3	-0.6	-0.6
India (Red Meat)	1.7	12.5	-	-0.03	+0.6	-	+0.3	-
USA (Poultry)	50.0	20.3	15.3	+0.2	-1.8	-2.0	-0.8	-0.9
China (Poultry)	38.6	19.7	13.8	+0.9	-1.1	-1.5	-0.5	-0.7
India (Poultry)	1.9	19.0	3.8	+0.08	+1.0	+0.1	+0.5	+0.1
USA ($Milk_{eq}$)	255	109	290	+0.03	-8.6	+2.1	-3.9	+0.9
China ($Milk_{eq}$)	33.2	99.6	115	+1.8	+3.9	+4.8	+1.8	+2.2
India ($Milk_{eq}$)	84.5	95.8	111	+1.5	+0.7	+1.5	+0.3	+0.7

Table 2: Dietary convergence trends from current food demand towards WHO or national dietary guidelines by 2030 and 2050. Convergence pathways in red meat, poultry; and $milk_{eq}$ for the average USA, Chinese and Indian dietary supply in 2013 to reach WHO healthy and national recommended diets by 2030, or 2050. Since food supply metrics are based on food demand (which equates to food intake plus household waste), WHO and national guidelines have been adjusted to reflect current regional household waste percentages from Gustavsson et al. (2011). Convergence patterns are given as the annual rate of change needed to reach guideline diets by the target year. The current (average trend since 2000) rate of change in intakes is also shown for comparison.

Unlike meat recommendations, the convergence pathways for dairy consumption vary significantly between WHO and USA guidelines. Average dairy consumption in 2013 in the USA was 255 $kgyr^{-1}$, approximately in line with the USA's recommendations. Consumption has remained almost constant over the last decade (with a small average increase of 0.03 $kgyr^{-1}$). Therefore, no change in average intakes would be necessary to meet USA guidelines. This is strongly divergent from WHO recommendations; meeting these guidelines would require a consistent reduction rate of 8.6 $kgyr^{-1}$ by 2030, or 3.9 $kgyr^{-1}$ by 2050.

Similarly to the USA, China's recent reduction in recommendations for red meat consumption now aligns its guidelines closely with the WHO healthy diet. Over the past decade, China's average demand for red meat has approximately stabilised. However, to reach recommended levels, this would have to reduce at approximately 1.4 $kgyr^{-1}$ to converge by 2030, or a reduced rate of 0.6$kgyr^{-1}$ for 2050. In contrast, its average poultry demand has been increasing at approximately 0.9 $kgyr^{-1}$. To converge on recommended levels, its annual rate of reduction would have to be between 1.1 and 1.5 $kgyr^{-1}$ for 2030, and 0.5 and 0.7 $kgyr^{-1}$ for 2050 (depending on whether convergence is set by WHO or Chinese guidelines). China's per capita dairy demand is particularly low relative to other transitioning and high-income nations at only 33 $kgyr^{-1}$ in 2013. Intake has, however, been growing at an average rate of 1.8 $kgyr^{-1}$. This rate of growth is well below 'target-meeting' growth rates of 3.9 and 4.8 $kgyr^{-1}$ which could be sustained to reach dairy recommendations by 2030. To converge on the healthy diet guideline by 2050, China's average demand could increase at a rate of 1.8 and 2.2 $kgyr^{-1}$. In other words, China could maintain its recent growth in dairy consumption and only just meet dietary guidelines by 2050.

India's pathways are notably different from those of the USA and China. Here, we have mapped the guidelines of India's non-vegetarian diet (where one daily portion of pulses is replaced with a source of animal-based protein). Even in this case, a clear divergence between Indian and WHO recommended pathways in red meat and poultry consumption is overt. It should be noted that average per capita demand of all meats is very low, at only 3.5 $kgyr^{-1}$. Further still, average red meat demand has shown a slow downward trend over the last decade. Poultry consumption has been growing very slowly at an average of 0.08 $kgyr^{-1}$; this growth could be maintained through to 2050 and still fall under WHO recommendations. In contrast, India's growth in milk demand (1.5 $kgyr^{-1}$) is higher than both WHO and national guidelines for convergence by 2030 or 2050. This is an important trade-off in India's lactovegetarian preferences, with milk forming the key source of high-quality protein. Whilst this may raise concern over its ability to meet dietary GHG targets, even in the case that milk consumption continued to grow to 140 $kgyr^{-1}$, and poultry consumption accelerated to WHO recommendations of 18 $kgyr^{-1}$, India's per capita footprint would equate to 912 $kgCO_2e$ $capita^{-1}yr^{-1}$. This is still well below the 1200 $kgCO_2e$ $capita^{-1}yr^{-1}$ footprint of the WHO healthy diet. In other words, if we were to define an equitable per capita dietary budget at WHO healthy diet levels, India's average diet is unlikely to exceed this, even under growth to 2050.

4. Conclusion

4.1 National dietary guidelines are incompatible with climate mitigation targets

Our analysis highlights the incompatibility of current national dietary guidelines for long-term climate change commitments and our nearer-term SDG targets. This inadequacy occurs for multiple reasons. Firstly, many national guidelines are vague or difficult to follow in their recommendations—a lack of quantification in terms of numbers of portions and portion sizes (especially for animal-based products) makes it challenging for individuals to adopt. If, at a global level, we are to promote dietary habits which are both nutritious and sustainable, clearer and more explicit guidance on dietary choices, quantities and substitutions need to be adopted at national levels.

Secondly, there is a clear lack of harmonisation in guidelines for both health and environmental sustainability outcomes. As previously reported, only a few contain any explicit mention of environmental considerations (Fischer & Garnett 2016). Upon quantification, we have shown that the national guidelines of several countries—the USA and Australia, in particular—are poorly aligned with GHG mitigation requirements. Global convergence on the USA's recommended diet, for instance, while potentially meeting health criteria, would result in a large increase in global GHG emissions. In fact, the adoption of this recommended diet would provide minimal GHG savings relative to the high emissions scenario of our BAU pathway.

With the exception of Indian and WHO healthy diet recommendations, all per capita emissions resultant from dietary guidelines exceed the average per capita budget (for all sectors, including energy and transport) necessary to meet a 1.5°C target. All guidelines fall within the total per capita GHG budget for a 2°C target, but would leave little room for emissions from other GHG-emitting sectors. As such, we conclude that the majority of current national guidelines are highly inconsistent with a 1.5°C target, and incompatible with a 2°C budget unless other sectors reach almost total decarbonisation by 2050. Global convergence (which is necessary to meet SDG2 of ending malnutrition—inclusive of undernourishment, micronutrient deficiency, and overconsumption) on current national guidelines would therefore fail to meet requirements within the Paris Agreement, and SDG13 of meeting these climate mitigation targets. If these are to be achievable, guidelines will have to be reframed to incorporate environmental and climate considerations.

Whilst national guidelines are inadequate in providing clear guidance on nutritious, climate-compatible diets, there may also be evidence that current WHO guidelines may need to be re-evaluated within context on their compatibility with health and climate targets. From a climate mitigation perspective, emissions from convergence on the WHO healthy diet would consume almost all of a global 1.5°C GHG budget. Under this dietary scenario agricultural and food production would dominate total GHG emissions within a global 2°C budget. Such guidelines are therefore only consistent with our climate commitments if rapid decarbonisation is achieved across other economic sectors.

There may also be evidence that an adaptation of current WHO recommendations would achieve health benefits. The World Health Organization currently set guidelines for red meat consumption on a maximum threshold basis as a result of strong links to non-communicable disease prevalence and mortality. However, recent long-term cohort studies show links between both unprocessed and processed red meat consumption (increasing with intake, but with no lower threshold) and cause-specific mortality from nitrate/nitrite and heme iron intake (Etemadi et al. 2017; Potter 2017; Pan et al. 2012). Etemadi et al. (2017) show that even when maintaining similar levels of total meat intake, the substitution of red with white (particularly unprocessed) meat shows notable reductions in mortality risk from cause-specific factors. Pan et al. (2012) also show the link between red meat consumption and an increased risk of cardiovascular disease (CVD), and cancer mortality, and the ability of substitution with other high-quality protein sources to reduce mortality risk. Such results raise further contention on the optimality of current WHO guidance—further reduction of their current maximum guidelines for red meat intake could further improve health and nutritional outcomes whilst also promoting dietary habits with greater climate mitigation potential.

4.2 Culture, social norms and drivers of change

Despite the incompatibility of current dietary guidance with climate and SDG targets, our analysis shows that for many countries current consumption patterns still greatly exceed these recommendations—particularly in terms of red and processed meat intake. Although slowly decreasing across many Western countries in particular, our results suggest that rates of decline would have to increase between five- and ten-fold to reach recommended levels by 2030 or 2050. A dramatic shift in consumer attitudes to meat consumption would therefore be required.

There are a number of important contributing factors to consumer food and meat choices (Bakker & Dagevos 2012). There is a strong positive relationship between income and meat consumption, which explains many of the large global inequalities in consumption (Kearney 2010). However, even when corrected for income, we see differing patterns of meat consumption (ibid).

Culture has historically played, and continues to play, a crucial role in food and dietary patterns. Meat consumption in particular has strong cultural links to a number of values including prosperity, masculinity, heath and indulgence (Ruby & Heine 2011; Boer et al. 2008). Religion has also had a large impact on meat trends; India's largely lactovegetarian preferences (reflected in its national dietary guidelines presented in this paper) are strongly linked to cultural and religious values (Bonne, Karijn et al. 2007; Devi et al. 2014).

The rise of "flexitarians" (or meat-reducers) across a number of countries provides a positive signal of cultural and social change with respect to meat consumption (Dagevos & Voordouw 2013). Nonetheless, this cultural and social transition with regards to meat consumption in recent years—as profiles of current consumption show in our analyses—are proving too slow to achieve the rate of change needed to meet our climate mitigation targets. Such significant change will have to be achieved through the adoption of a range of economic and behavioural strategies.

There have been a number of options proposed to accelerate reductions in meat (particularly red and processed meat) consumption. There continues to be a strong case for consumer education, not only with respect to the environmental impacts of meat, but combining these with education on health and nutrition. Consumer surveys have shown that a substantial obstacle for meat reduction with a high number of consumers is the image of meat as a healthy food product; many admit they are reluctant to substitute meat out of their diet through concerns of protein and nutritional imbalance (Bakker & Dagevos 2012). Consumer messaging strategies are likely to be more influential when they extend beyond the GHG benefits of reduced meat consumption, and instead focus on important co-benefits such as health and wellbeing (Wellesley et al. 2015).

Economic drivers of change could also play a role in shifting diets. Springmann et al. (2016) show that substantial GHG reductions could be achieved through taxation and commodity pricing based on carbon intensity of food products (Springmann, Mason-D'Croz, et al. 2016). If effectively designed, they show that both GHG reduction and health benefits can be achieved across high-income and most middle and low-income countries—however, this could require significant political backing. Meat substitute (such as mycoprotein, in-vitro meat, and soya-based) products could also play a role in shifting towards lower-carbon diets (Joshi & Kumar 2016; Smetana et al. 2015). To prove competitive to meat products, these substitutes will likely have to achieve notable price reductions, either through subsidy mechanisms, taxation or technologically-driven efficiency and cost cuts (Ritchie et al. 2017).

We conclude that nutritional and climate goals are currently incompatible. Aligning nutritional goals and internationally agreed climate change targets will therefore require major reframing of social norms towards dietary preferences and consumption patterns, but also further evaluation of global and national-level guidance on recommended dietary intakes.

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Chapter Six:
Potential of meat substitutes for climate change mitigation and improved human health in high-income markets

After article: Ritchie, H., Reay, D. S., & Higgins, P. (2018). Potential of meat substitutes for climate change mitigation and improved human health in high-income markets. *Frontiers in Sustainable Food Systems*, 2, 16. doi: 10.3389/fsufs.2018.00016

Abstract

The global food system is estimated to contribute approximately one-quarter of greenhouse gas (GHG) emissions—this is dominated by the livestock sector. The projected increase in livestock demand is likely to undermine efforts to keep global average warming below a 2°C target. A carbon tax is often proposed as the preferred demand-side mechanism for reduced meat consumption. Previous studies, however, suggest that while this could prove successful in reducing net global emissions, it may worsen nutritional standards in lowest-income nations. An alternative market mechanism which may simultaneously reduce GHG emissions and improve health at all income levels is a reduction in the price of meat substitute products. Using a coupled ecological and health modelling approach, we project the associated GHG savings and health benefits associated with a stepwise reduction in the price of meat substitute products. Utilising food demand elasticities, we quantify the substitution of meat commodities across a range of social acceptability scenarios. Our results show that meat substitute products have a large potential for reducing GHG emissions (up to 583MtCO_2e per year) and improving nutritional outcomes (up to 52,700 premature deaths avoided per year). However, this capacity is strongly dependent on a combination of price reductions and improved social acceptability of this product group—both will be essential to do so.

1. Introduction

Agriculture and food production are estimated to contribute approximately 25-30% of global greenhouse gas (GHG) emissions, dominated by the livestock sector which accounts for an estimated 14.5% globally (IPCC 2014; World Watch Institute 2009). Meat consumption shows strong coupling to economic growth (Fiala 2008); as a result, the combination of continued population growth and economic development means global meat consumption is projected to increase by 75-80% by 2050 (Wellesley et al. 2015). Without a significant reduction in the GHG-intensity of livestock production, it's likely that this level of meat consumption will undermine efforts to keep average global warming below 2°C (as targeted within the UN Paris Agreement (UNFCCC 2015)) in the 21st century (ibid). Mitigation within the livestock, and broader agriculture sector, will therefore be essential in meeting global climate targets.

Meat consumption can have both positive and negative implications for nutrition and sustainability. Whilst animal-based products generally have a higher GHG emissions-intensity relative to plant-based food commodities, moderate consumption of meat and dairy products can have a significant positive impact on human health and nutrition, providing high-quality protein, complete amino acid composition, and a vital source of micronutrients such as iron, calcium, zinc and vitamin B_{12} (Wu et al. 2014). This is particularly important in developing nations where per capita meat intake is often lower than in developed nations, and where dietary composition is typically dominated by micronutrient-poor cereals and starchy roots (Gómez & Ricketts 2013). Even small amounts of meat supplementation to the diets of low-income households has been shown to have nutritional benefits and reduce severe malnourishment indicators such as childhood stunting (Rivera et al. 2003). In contrast, the overconsumption of meat within the typical Western diet can have severe negative health implications, including increased risk of chronic diseases such as cardiovascular disease, stroke and some forms of cancer (also known as 'non-communicable diseases'; NCDs) (Walker et al. 2005).

Being able to simultaneously address the second United Nations Sustainable Development Goal - SDG2 (zero hunger and malnutrition) and SDG13 (urgent action to combat climate change) will require a convergence of meat consumption trends: a sustainable increase in intakes within developing nations, and a significant decrease in per capita consumption within the typical high-income diet. The ability to simultaneously enhance global GHG mitigation efforts and improve human nutritional health would be a notable win-win scenario for society; all the more significant due to the timescale over which the SDGs are to be achieved (2015-2030).

While a number of demand management policies and market-based levers have been suggested to reduce average meat intakes, a carbon taxation on food commodities is often recommended as the preferable approach (Cuevas & Haines 2016). Since animal-based products tend to have a higher carbon footprint than plant-based alternatives, they would experience a proportionally higher price increase under a carbon taxation scheme, potentially driving consumers towards alternatives with a lower carbon-intensity.

Results of the first (and only, to date) global assessment of the GHG mitigation and health impacts of emissions pricing of food commodities indicate that levying GHG taxes could have a synergistic positive impact on human health and emissions reduction across most countries—particularly high and middle-income nations (Springmann, Mason-D'Croz, Robinson, Wiebe, et al. 2016). The key potential drawback to such a tax-based mechanism is a negative nutritional impact on low-income nations and households; even in regionally-optimised tax scenarios, emissions pricing would result in an increase in the prevalence of underweight individuals (ibid). These negative impacts may be more concerning still if overall dietary quality, including high-quality protein, fat and micronutrient intake, were assessed—a food commodity tax may push low-income groups further towards a low-cost cereal-dominant diet (Gómez-Galera et al. 2010; Gómez & Ricketts 2013). This outcome is analogous to the findings of taxation impact studies on energy policy: low-income nations tend to benefit from supply-side policy measures (such as targets and standards) rather than demand-side policies (Zhang & Wang 2017). Therefore, while a food carbon tax would result in promising GHG reductions and provide a *net* human health benefit globally, the negative consequences for low-income groups and regions cannot be ignored if SDG2 is also to be addressed.

An alternative market mechanism which may support both improved nutrition and GHG mitigation at all income levels, is a significant decrease in the market price of meat substitute products. Meat substitutes (also termed 'meat analogues' or 'meat-free alternatives') are products which share aesthetic and chemical qualities (such as texture, taste and appearance) with certain meat products (Joshi & Kumar 2016). The meat substitute market has grown strongly in recent years, largely due to increasing awareness of the purported health and ecological benefits of reduced meat consumption (MINTEL 2014). Despite continued growth, the overall market share of meat substitutes is small, with only 3-5% of the meat market in Europe (MINTEL 2013). There are a number of social challenges to the uptake of meat substitute products, however, one of the largest barriers is their often high price relative to the meat products they are intended to replace (Apostolidis & McLeay 2016). This provides no economic incentive for substitution, relying on social motivations alone—as a result meat substitutes typically occupy a niche, premium segment of the market (Ritchie et al. 2017).

Financial incentives have been highlighted as one of the prime mechanisms which may be utilised to drive a larger transition towards meat substitutes (Apostolidis & McLeay 2016). These could involve financial interventions such as subsidisation, however, a more sustainable scenario would be of a natural reduction of meat substitute production and retail costs through technological innovation and efficiencies of scale. A range of meat substitute products are at the stage of technological development, with the commercialisation of a growing number of products in turn helping to create a more competitive market. As a result, the unit cost of these products is likely to decrease with time. For example, a proposed process innovation in the production of mycoprotein (the base protein component of the global branded leader Quorn™) is expected to halve current production costs (Ritchie et al. 2017), potentially making the unit cost to consumers lower than meat alternatives.

Meat substitutes have the potential to simultaneously address SDG2 (zero hunger) and SDG6 (clean water and sanitation) since they not only have a lower (and declining) carbon-intensity relative to most meat products, but can also offer significant nutritional benefits. Plant-based proteins typically provide high-quality protein with high digestibility and amino acid scoring and a range of key micronutrients, but with a lower caloric and fat content relative to animal-based proteins (Denny et al. 2008). A low-cost supply of sustainable protein could therefore help to avoid the drawback of a carbon taxation scheme: it would carry similar nutritional benefits for reduction in NCD risk factors and obesity in meat-intensive diets, but would also help to address protein and micronutrient malnutrition in low-income nations.

While the sustainability and nutritional benefits of meat substitute products are often highlighted at an individual dietary level (Denny et al. 2008; Smetana et al. 2015), no comprehensive analysis has been conducted on the overall scale of these benefits at the national, regional and international level.

Here we present what we believe is the first analysis of the magnitude of GHG mitigation and human health benefits which could be achieved through price reductions within the meat substitute sector. This analysis is based on a combination of meat price elasticity relationships with a range of social acceptability scenarios. Our assessment is based on the meat substitute product mycoprotein, which is currently sold solely under the brand name Quorn™. We have selected mycoprotein for several reasons: Quorn™ is currently the global branded leader in the meat analogue sector; in-depth life-cycle assessments (LCA) of the product are publicly available (Finnigan 2010; Smetana et al. 2015); and significant price reductions are deemed to be technologically realistic (Ritchie et al. 2017). However, the methodology and concept utilised in this paper could be readily applied to any similar meat substitute product.

2. Methods

2.1 Quantifying meat substitution rates

Two key variables were adjusted in this analysis: level of price reduction in meat substitutes, and level of social acceptability. In this analysis, mycoprotein in the form of bulk Quorn™ products was selected as choice of meat substitute; Quorn™ global branded leader in the meat analogue sector; and has in-depth life-cycle assessments (LCA) publicly available (Finnigan 2010; Smetana et al. 2015). Mycoprotein sales are currently limited to markets within Europe, the United States of America (USA), Australia, New Zealand and South Africa. While the expansion of meat substitute markets into additional high- to middle-income countries is likely, there has been little discussion of their potential emergence within developing nations. Social attitudes and acceptance of these types of products within developing nations is therefore insufficiently understood. For this reason, and in addition to poor data availability, the present study has focused on the quantification of meat substitution within higher-income markets. However, the potential for meat substitute products within lower-income and transitioning economies is further discussed here and, in our view, deserves more attention. Our assessment considers potential impacts across 40 high-income countries which are either existing markets for mycoprotein, or are likely to be in the near future (see Table A1). Scenarios are focused on the year 2020—a near-term date by which time lower-cost meat substitute products may realistically become commercialised.

Our analysis considers the price-induced changes in consumption which would occur through incremental price reductions of meat substitutes from present-day prices. This is modelled based on cross-price elasticities, which measure the change in demand for one 'good', based on a price change in another (Cornelsen et al. 2014).

The level of meat substitution, and resultant changes in consumption were generated modelled using economic demand elasticity methods. Cross-price elasticities were utilised from one of the most up-to-date assessments of demand variations with price, income and product category (Lusk & Tonsor 2016). Credible data on the cross-price elasticity of demand for meat substitute products is scarce. In this assessment, we have therefore utilised cross-price elasticities of meat products relative to a price reduction in chicken—which is the lowest cost, and often considered lowest quality, of meat products in the regions considered (Lusk & Tonsor 2016).This demand elasticity assessment was based on choices made by 12,255 US consumers across low, middle and high-income levels. In our 'perfect' substitution scenario (scenario 1), cross-price elasticities have been applied based on change in demand relative to a price reduction in chicken (with chicken being the cheapest form of meat). To map the effect that meat substitutes would have on chicken demand, we have applied cross-price elasticities of high-quality chicken with lower-quality, cheaper chicken cuts.

It cannot be assumed that consumers would respond to a price reduction in meat substitutes in the same way that they would to the same reduction in chicken. To account for this uncertainty, we have modelled five scenarios which reflect differing levels of social acceptance of mycoprotein as a viable meat substitute. Scenario 1 is based on a high level of social acceptability, and assumes a perfect reflection of chicken cross-price elasticities (i.e. that consumers respond to price reductions in meat substitutes in exactly the same way as they do to chicken). Scenarios 2 and 3 are based on a medium and low level of social acceptability, respectively. Results are based on a respective 50% and 25% change in substitution relative to scenario 1 (perfect substitution). Scenarios 4 and 5 are ambitious, but have been included to cover the possibility of increased social preference relative to chicken—they assume a 125% and 150% change in substitution relative to scenario 1 results, respectively. These scenarios would reflect the case where meat substitutes became increasingly preferred over meat as a result of increased health, nutrition and sustainability concerns. Achieving such a drastic change in consumer preference would require significant governmental and advisory input. Note that the results of this study report the *additional* price-induced changes in consumption, which will allow for market penetration to the average consumer; it is acknowledged that in scenarios 1-3, meat substitutes will already hold a share—albeit small—of the market.

The five social acceptability/preference scenarios are summarised below:

Scenario 1 = high social acceptability = perfect substitution (i.e. consumers respond to a price decrease in meat substitutes in the same way as they would with chicken);

Scenario 2 = medium social acceptability = cross-price elasticities are assumed to be 50% of those utilised in scenario 1 (i.e. consumers are only half as responsive to a change in price);

Scenario 3 = low social acceptability = cross-price elasticities are assumed to be 25% of those utilised in scenario 1 (i.e. consumers are only one-quarter as responsive to a change in price);

Scenario 4 = social preference = cross price elasticities are assumed to be 125% of those utilised in scenario 1 (i.e. consumers are 25% more responsive to a change in price due to positive social attitudes);

Scenario 5 = high social preference = cross price elasticities are assumed to be 150% of those utilised in scenario 1 (i.e. consumers are 50% more responsive to a change in price due to positive social attitudes).

Price reductions are mapped in five percent increments from a 5% to 75% reduction in the average 2015 market price of standard Quorn™ products ($US8.52 per kg) relative to chicken (US$7.52 per kg) from World Bank data. As is shown in results of scenarios 1-3, standard market prices of Quorn™ products are 10% more expensive than chicken per unit, meaning no substitution effect occurs until these products reach price-parity. This relative price reduction is then multiplied by cross-price elasticity values to attain changes in consumption of each of the meat commodities (beef, pigmeat, chicken and sheep). To calculate total reductions in consumption, business-as-usual (BAU) baseline emissions were first calculated based on projected per capita meat intake (by commodity) (OECD 2016) and UN Population Division projections in 2020 (United Nations 2015) for each country included in this study (see Table A1). Reductions in meat consumption were then calculated based on changes in consumption relative to BAU levels.

2.2 Quantifying greenhouse gas (GHG) reductions

To convert changes in meat consumption to changes in GHG emissions, we used commodity-specific GHG intensities (kgCO_2e/kg product). We adopted average FAO livestock emission factors measured and reported across the full value chain, from farm-gate to retail sale (see Table A3) (Gerber et al. 2013). The assessed GHG intensity of mycoprotein in the form of Quorn™ products was adopted from full life-cycle analysis (LCA) assessments—these evaluations extend beyond the footprint of the mycoprotein base product to the total GHG intensity of production of the final marketable product (Finnigan 2010; Smetana et al. 2015). GHG emissions savings were calculated based on baseline emissions levels which would be expected from BAU 2020 meat consumption intakes versus emissions which would result with meat substitution included.

2.3 Quantifying health impacts

Our health analysis replicated the standard methods utilised in Springmann et al.'s (2016) assessment of mitigation potential and health impacts from emissions pricing (Springmann, Mason-D'Croz, Robinson, Wiebe, et al. 2016). This methodology utilises a global comparative risk assessment framework (Springmann, Mason-D'Croz, Robinson, Garnett, et al. 2016). In this analysis, we included only health risk factors directly related to meat, and red meat consumption, in addition to weight-related risks as a result of changes in body mass index (BMI). This utilised population attributable fractions (PAFs) which measure the number of negative health cases which would resultant in any given scenario versus those in a baseline/BAU condition (Lim et al. 2012). Relative risk factors for coronary heart disease (CHD), stroke and cancer in relation to diet- and weight-related factors were derived from pooled meta-analyses (Prospective Studies Collaboration et al. 2009; Micha et al. 2010; Chen et al. 2013; World Cancer Research Fund & American Institute for Cancer Research 2007) (see Appendix 1 for extended methods). Mortality rates were assumed based on data from the Global Burden of Disease project, which measures the prevalence of deaths by cause across 20 age groups (Lozano et al. 2012). To quantify the overall health implications, these have been reported as number of premature deaths avoided.

3. Results

3.1 Meat substitution rates

Our results show a strong sensitivity to both key variables analysed in this study: the magnitude of price reduction and level of social acceptance of meat substitutes. The change in consumption of the different meat commodities (beef, pigmeat, poultry and sheep) relative to projected 2020 levels, for each of the scenarios is represented in Figures 1a-e. Note that in scenarios 1-3, where the social acceptability or preference for meat substitutes is equal or less than that of chicken, no substitution effect occurs until prices decrease by more than 10%; this represents the level at which chicken and Quorn™ mycoprotein reach price parity. Under these scenarios, we therefore assume that consumers would still prefer to substitute other forms of meat with chicken rather than mycoprotein. In scenarios 4 and 5, we assume that consumers actually prefer mycoprotein over chicken and would therefore continue to substitute, even if mycoprotein was more expensive.

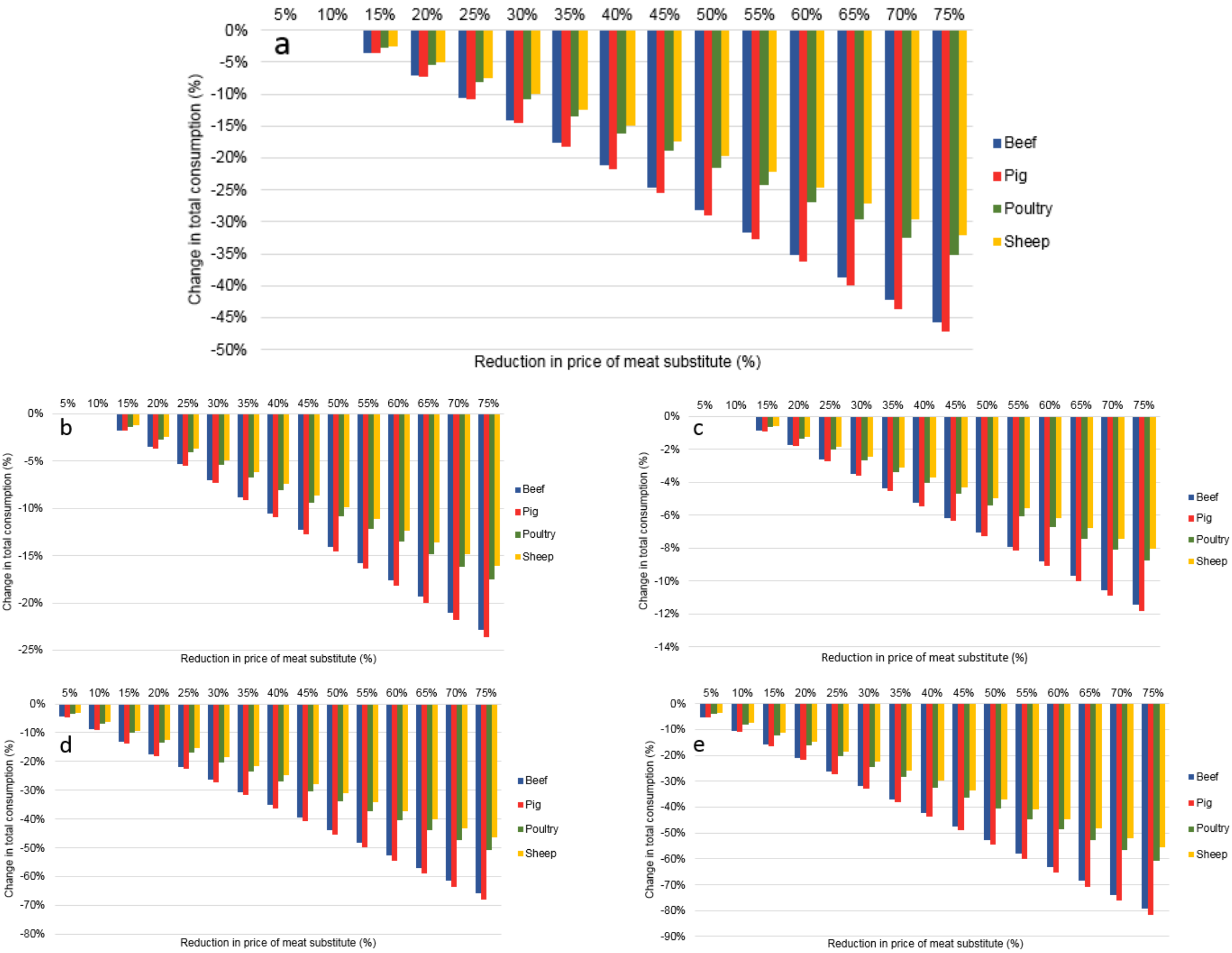

Figure 1: Changes in consumption of meat commodities through substitution with mycoprotein. Percentage changes in consumption of meat commodities as a result of substitution with mycoprotein, or alternative meat substitute products, across a range of price reduction assumptions in (a) scenario 1; (b) scenario 2; (c) scenario 4; (d) scenario 4; and (e) scenario 5.

Under all scenarios we see that the composition of substitution between the various meat commodities remains constant, with the percentage change in pigmeat consistently highest, followed by beef, poultry and sheep meat. The magnitude of this substitution effect, however, shows significant variability. In the case of perfect substitution (scenario 1), our maximum consideration of a 75% decrease in price would result in approximately 40-45% reduction in beef and pigmeat consumption. At a more realistic target of a 50% reduction in price, substitution would result in a 20-30% reduction across all individual meat commodities. Our results show that the social acceptability variable is highly significant: at low levels of social acceptability (scenario 3), even if meat substitute prices were to decline by 75%, substitution would be low at less than 12%. In contrast, if there was strong consumer preference towards meat substitutes, this substitution effect could be as high as 60-80% for all individual commodities.

3.2 Greenhouse gas (GHG) reductions from meat substitution

Table 1 and Figure 2 detail the resultant GHG emissions savings which would occur under each of the scenarios and price decline assumptions. In line with our results of changes in meat consumption, in scenarios 1-3, no additional GHG savings would occur as a result of a price decrease below 10%. Annual GHG reductions show large variability across the five scenarios, ranging from a low of 48MtCO_2e at 75% price reduction in scenario 3 to 583MtCO_2e in scenario 5. For reference, we estimate (based on average GHG intensities, national per capita meat consumption and population figures in 2020) baseline emissions from meat commodities in countries included in this study to be 950MtCO_2e.

To illustrate how GHG savings are distributed geographically and across the commodity types, this breakdown has been shown in Figures 3a-b for Scenario 1. This breakdown by region highlights that GHG reductions would be dominated by the USA and EU28 markets—this is promising given that these are the markets in which mycoprotein sales are currently highest. When summarised by meat commodity, we observe that GHG savings are dominated by beef substitution, accounting for approximately the same as pigmeat and poultry combined. Emissions savings potential from sheep substitution is relatively small. Note that GHG emissions resulting from mycoprotein production (in the form of Quorn™) are here shown as negative savings; how these emissions may evolve with time is further discussed in Section 4.

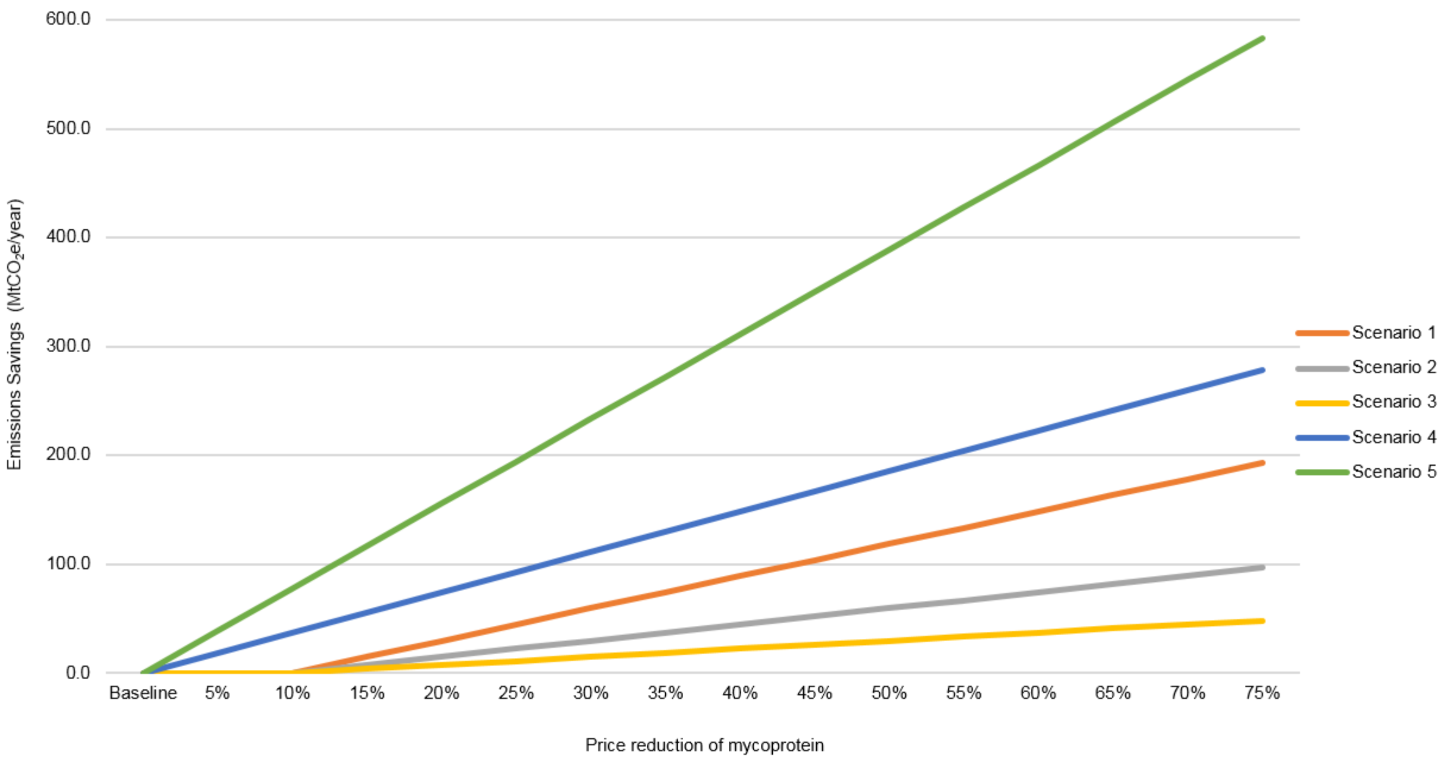

Figure 2: Greenhouse gas emissions savings as a result of meat commodities substitution with mycoprotein. Total greenhouse gas reductions, measured in $MtCO_2e$, across the countries modelled in this study by level of price reduction and social acceptability scenarios.

Percentage price reduction from 2015	***5%***	***10%***	***15%***	***20%***	***25%***	***30%***	***35%***	***40%***	***45%***	***50%***	***55%***	***60%***	***65%***	***70%***	***75%***
Scenario 1	0.0	0.0	31.4	29.7	44.5	59.3	74.2	89.0	103.8	118.7	133.5	148.3	163.2	178.0	192.8
Scenario 2	0.0	0.0	7.4	14.8	22.3	29.7	37.1	44.5	51.9	59.3	66.8	74.2	81.6	89.0	96.4
Scenario 3	0.0	0.0	3.7	7.4	11.1	14.8	18.5	22.3	26.0	29.7	33.4	37.1	40.8	44.5	48.2
Scenario 4	18.5	37.1	55.6	74.2	92.7	111.3	129.8	148.3	166.9	185.4	204.0	222.5	241.1	259.6	278.1
Scenario 5	38.9	77.8	116.7	155.5	194.4	233.3	272.2	311.1	350.0	388.9	427.7	466.6	505.5	544.4	583.3

Table 1: GHG emissions saving by percentage price reduction in mycoprotein across five social acceptability scenarios. Greenhouse gas emissions reductions, measured in $MtCO_2e$, as a result of meat substitution effects with mycoprotein ranging from a 5% to 75% price reduction from 2015 prices. Scenarios 1-5 are representative of the social acceptability assumptions utilised in this study.

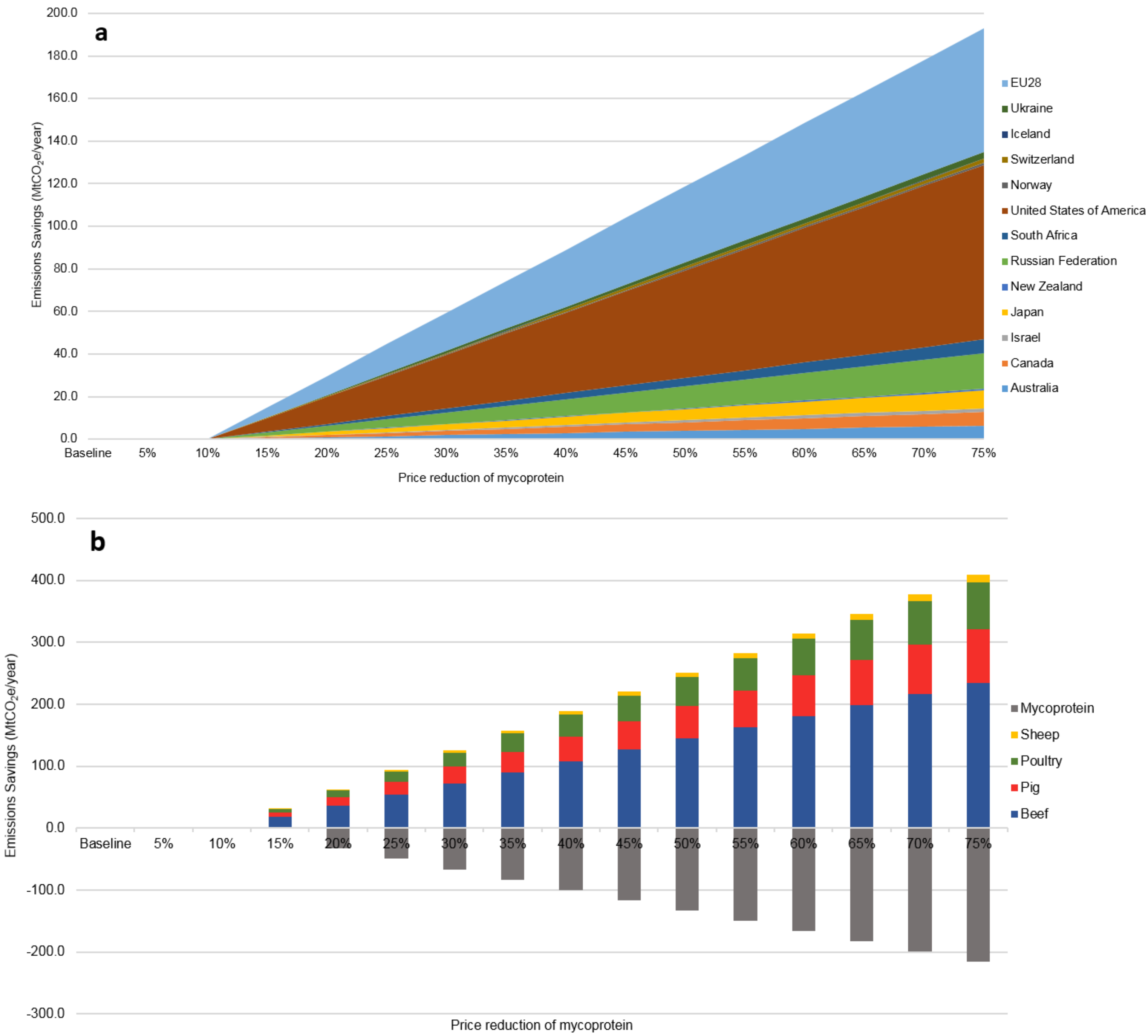

Figure 3: Greenhouse gas emissions savings in scenario 1, broken down by country/region and meat commodity. Annual GHG emissions savings ($MtCO_2e$), represented as a breakdown by (a) country or region; and (b) type of meat commodity substituted. Note that emissions associated with the production of mycoprotein have been shown as negative savings.

3.3 Health impacts of meat substitution

Table 2 details the projected health impacts of substitution in terms of number of premature deaths avoided, by scenario and level of price reduction in mycoprotein. In a perfect substitution case (scenario 1), the number of avoided deaths ranges from zero at <10% price reduction, to approximately 38,300 at 75%. At this upper price reduction limit, the number of deaths avoided ranges from a low of approximately 8500 in scenario 3, to 52,700 in scenario 5. Mycoprotein has a lower caloric content relative to meat products (Table A2), therefore straight dietary substitution by mass would have an impact on average BMI and obesity reduction. While there are notable health improvements projected through these weight-related factors, the number of deaths avoided in this analysis is dominated by diet-related factors (reduction of risk of NCDs linked to meat and red meat consumption). In all scenarios, diet-related factors were responsible for >85% of the number of deaths avoided. Figure 4 illustrates the breakdown of number of deaths avoided by region in scenario 1; trends reflect those seen in GHG emissions reductions with strong dominance of health improvements in the USA and EU28.

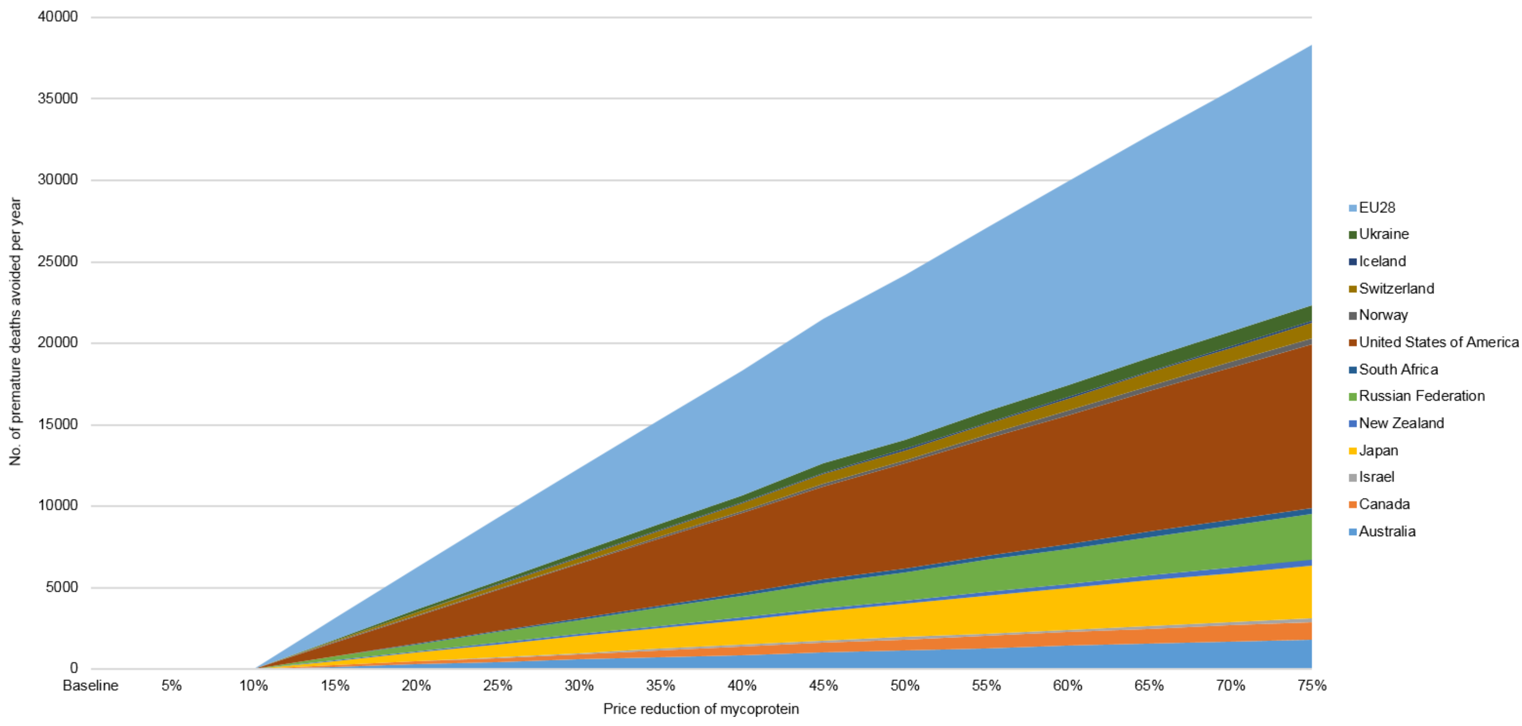

Figure 4: Number of premature deaths avoided in scenario 1, by country/region. Health benefits, quantified as the number of premature deaths avoided per year in scenario 1, as a breakdown by country or region.

Percentage price reduction from 2015	***5%***	***10%***	***15%***	***20%***	***25%***	***30%***	***35%***	***40%***	***45%***	***50%***	***55%***	***60%***	***65%***	***70%***	***75%***
Scenario 1	0	0	3139	6244	9315	12354	15360	18334	21526	24189	27069	29920	32741	35532	38294
Scenario 2	0	0	1807	3362	4909	6448	7979	9501	11015	12521	14019	15509	16991	18465	19931
Scenario 3	0	0	881	1519	2154	2789	3422	4054	4685	5315	5943	6569	7195	7819	8442
Scenario 4	3413	6550	9656	12730	15773	18785	21768	24720	27643	30538	33403	36241	39050	41833	44588
Scenario 5	4043	7796	11504	15167	18785	22361	25893	29383	32832	36241	39609	42938	46228	49480	52695

Table 2: Number of deaths avoided as a result of meat substitution with mycoprotein across the range of price reduction and social acceptability scenarios. Health benefits, measured as the number of deaths avoided, across the range of countries modelled in this study. Improved health outcomes result from a reduction in non-communicable diseases and obesity reduction through meat substitution.

4. Discussion

This study has attempted to provide the first quantification of GHG mitigation and human health benefits of meat substitutes across a range of economic and social acceptability scenarios, and has done so for the year 2020. It is worth noting that, with time, we would expect the potential for net GHG mitigation to increase for a given level of meat substitution based on reduced emission intensity of mycoprotein production. Quorn™ mycoprotein products have a footprint of approximately 5.6kgCO_2ekg^{-1}, which is significantly lower than beef and sheep products but comparable to the global average for poultry of 5.7kgCO_2ekg^{-1} and only marginally better than pigmeat at 6.1kgCO_2ekg^{-1}. So while the substitution of poultry and pigmeat could be significant, the embedded emissions in mycoprotein production typically offset any expected GHG savings.

We would expect the GHG footprint of industrial meat substitute production to decrease with time through technological innovations and efficiency improvements. Even in the unlikely case that improvements in process design and efficiency were not realised, since a large component of its industrial footprint lies in energy consumption (Smetana et al. 2015), its carbon-intensity should decline by default through progress in energy decarbonisation. This is in contrast to livestock production where emissions are dominated by non-CO_2 gases (Gerber et al. 2013), and farming systems have already been heavily intensified in high-income countries (Robinson et al. 2011).

Our results have highlighted the sensitivity of the potential impact of meat substitutes to both economic and social acceptability factors. Our analysis suggests that meat substitutes are unlikely to gain a substantial share of the meat market unless their relative price declines significantly—this is apparent even in scenarios where social acceptability is high. A transformative shift in meat substitute production and its economic structure is therefore likely to be necessary if this group of food products is to make notable contributions to GHG mitigation and human health improvements. Equally crucial is a shift in public perceptions and attitudes towards this group of products; our results show that substitution effects would be marginal, even if relative prices were to decrease by 75%, in scenarios with poor social acceptability. Improving public acceptability of, and preferences for, meat substitute products—whether via sustainability or nutritional justifications—will also be essential. This combined transformation will be of prime importance to industry and businesses working within the meat substitute sector, as, without a pairing of these drivers, market expansion will be limited.

Price reductions will be even more crucial if this market is to extend into developing and lower-income nations. The availability of industrially-produced meat substitutes in developing nations is negligible to non-existent, and therefore excluded from this study. However, the potential for coupled GHG mitigation and human nutritional improvements in these regions is arguably higher than in high-income nations. Global increases in meat consumption (and sectoral GHG emissions) are projected to be driven primarily through increased intakes within lower-income and transitioning economies (Vinnari & Tapio 2009). If substitutes entered these markets below the price of meat commodities, this projected rate of increased meat consumption may be curbed. While high prices tend to be the largest barrier to meat consumption, surveys suggest that nutritional quality and concerns over product quality factor highly in consumer decisions (Raghavendra et al. 2009). The availability of a cheaper, quality-assured healthy source of protein may be well-received within such markets.

Nutritional benefits for lower-income households are a key differentiating factor between the potential of meat substitutes and a GHG food taxation method. While a carbon tax has the potential to exacerbate the issue of malnutrition at low incomes, progress in meat substitutes has the capacity to deliver high-quality proteins at low-cost. Crucially for populations where micronutrient deficiencies are common as a result of monotonous diets, the industrial production and processing of these products allows for low-cost fortification with essential vitamins and minerals (Gómez-Galera et al. 2010).

Meat substitutes therefore hold significant potential for GHG mitigation and improved nutrition across all income level. Indeed, this may be an effective mechanism by which SDG2 and SDG6 could be approached simultaneously through to 2030. To do so, significant progress will have to be achieved in technological innovation and efficiency - to realise lower cost production, and in improving consumer acceptability of meat substitute products.

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Chapter Seven:
Global greenhouse gas emissions from aquaculture

After article: Ritchie, H, Reay, D. Global greenhouse gas emissions from aquaculture. Aquaculture (submitted). As appears in Chapter Seven.

Abstract

There is a growing focus on the agricultural sector, and livestock production in particular, in its contribution to global greenhouse gas (GHG) emissions. However, the contribution of aquaculture has received far less attention. To date, no published estimates of total GHG emissions from aquaculture exist. Here, we provide a first estimate of global CO_2e emissions arising from aquaculture, using historic (1950-2013) FAO production trends combined with published species-specific emission factors. Projected emissions scenarios have also been mapped out through to 2030 based on historic growth rates, FAO and World Bank projections to assess aquaculture's evolving contribution to global emissions. We estimate 2013 emissions from global aquaculture to be 227±61 MtCO_2e, with an average annual growth rate of 8% over the 1950-2013 period. There is a strong dominance in emissions by region, and by aquaculture species group; 84% of emissions originate from only seven Asian nations (with China accounting for 57% of the global total). More than 90% of estimated emissions are produced from the top ten species groupings, with a strong dominance by 'carps and other cyprinids', 'shrimps', and 'miscellaneous freshwater fishes'. World Bank "Fish to 2030" projections estimate baseline global emissions of 365±99MtCO_2e by 2030—a 60% increase on 2013 levels. In our highest growth scenario, 2030 emissions increase to 901±243MtCO_2e, representing a four-fold increase. This indicates that, despite being comparably minor relative to total livestock GHG emissions (approximately 3-4%), global aquaculture will become increasingly important for climate change mitigation in the food production sector as a whole. Here we also highlight the research gaps that must be addressed for better understanding of mitigation potential and emissions estimation.

1. Introduction

Global agriculture represents one of the largest contributors to total greenhouse gas (GHG) emissions, and therefore human-induced global warming. The dominance of livestock emissions in this sector (estimated at 7.1 gigatonnes carbon dioxide equivalents (CO_2e) per annum—14.5 per cent of human-induced GHG emissions; FAO, 2013), has highlighted global meat consumption as a key focus for GHG mitigation (FAO, 2009; 2013; Herrero et al. 2015). However, to date, research has largely focused on terrestrial, rather than marine and freshwater, food production (Williams & Crutzen, 2010; Cochrane et al. 2009).

Fish production represents a key protein and food source for many—fish account for almost 17% of total global protein demand, reaching up to 70% in some coastal and island nations (FAO, 2014). The nutritional composition of fish in general—high protein content, comparatively low calorific value, density of micronutrients such as omega-3 fatty acids, iodine, selenium and co-enzymes (Cochrane et al. 2009)—can make it an important dietary component for addressing malnutrition at both ends of the spectrum (Thompson & Amoroso, 2011; Parra et al. 2007). Fish can also play a key role in the challenge of meeting increasing protein demands through lower resource consumption, with its typical feed conversion ratio (FCR) of 1.2-1.7 (Cao et al. 2015) being one of the lowest of all animal-based products (Cao et al. 2013).

Even within the limited literature on the sustainability of seafood production, aquaculture—the farming of aquatic species—comprises a minor component. Much of this can be attributed to the relative immaturity of commercial-scale aquaculture in many nations. However, aquaculture has undergone rapid growth in the last few decades, growing at a rate of 8.7% per year since 1970 (Williams & Crutzen, 2010) as production from capture fisheries has stagnated from overfishing and natural stock decline. It now supplies approximately half of global seafood harvest (FAO, 2014). It is projected that aquaculture growth rates will continue to remain high (Diana, 2009), as production from capture fisheries is likely to remain constant at best with possible declines due to environmental impacts such as climatic warming (Cochrane et al. 2009).

As the fastest-growing food sector, a fuller understanding of aquaculture's global GHG emissions and associated sustainability implications is urgently required. Research on the environmental evaluation of aquaculture has traditionally focused on its ecosystem and biodiversity impacts (Winther et al. 2009), rather than its climate change contribution. Although studies have been conducted on GHG emissions at a local level on fish farms or specific species, no estimates of global emissions have been published to date (Williams & Crutzen, 2010).

The key objective of this study was to provide a first global estimate of GHG aquaculture emissions by review of all available data. This serves several purposes: (1) to provide an initial context for the magnitude and distribution of current emissions; (2) highlight the magnitude of potential future emissions from the sector; and (3) identify the key literature and data gaps which must be addressed for more robust estimation, understanding and potential mitigation.

2. Methods

2.1 Estimating historical and current aquaculture emissions

Past and current global GHG emissions arising from aquaculture were estimated using combined annual FAO "FishStat" aquaculture production data (http://www.fao.org/fishery/statistics/software/fishstatj/en) (provided as a quantity in tonnes) and species-specific aquaculture emission factors (EF), derived from extensive literature review. Total emissions in a given year can therefore be estimated by multiplying the production quantity of a given species, by its species-specific emissions factor. Hence, the global greenhouse gas emissions (GHG) in a given year (y) is given by (Equation 1):

$$GHG_y = \sum (Q_1 * EF_1) + (Q_2 * EF_2) + (Q_3 * EF_3) \ldots (Q_n * EF_n)$$

where Q is the production quantity (measured in tonnes) of a given fish species, EF is a species-specific emissions factor ($kgCO_2e$/tonne production) and n represents the number of species categories.

FAO aquaculture datasets cover the period 1950-2013 and can be categorised by production by species, species category and/or country of production. We therefore applied a Tier 1 approach to emissions estimation (IPCC, 2006). For this study, in acknowledgement that emissions factors have not been extensively derived for the 310+ farmed fish species recorded by the FAO (Pelletier & Tyedmers, 2008), species were aggregated using the FAO's International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) grouping methodology; this presents aquaculture production data within 38 species groupings.

Emissions factors for species groupings were derived from extensive literature review of species-specific Life Cycle Analysis (LCA) studies conducted on single fish farms. Our own literature review was cross-referenced with the Seafish Industry Authority's review report of life cycle assessment research on products derived from fisheries and aquaculture (Parker, 2012) to ensure that all available published analysis had been included in our EF allocations.

In total, we included 34 LCA measurements referenced in the Seafish Industry Authority's review, in addition to 13 analyses not detailed in this report (LCA studies utilised in this study are detailed in Supplementary Table 1). All studies used an attributional LCA type, and are defined by a cradle-to-gate boundary scope; this measures emissions arising from farming activities (including all resource inputs) through to factory gate (prior to distribution to the consumer). In all studies, this scope covers fish feed (including embedded emissions in production of feed), energy (in the form of electricity use to run recirculating and aeration systems), nutrient and other infrastructural inputs required in the farming phase. To maintain consistency, LCA studies which failed to cover the full cradle-to-gate stage were omitted from our analysis.While post-gate (processing, packaging and transport to consumer) emissions are therefore not reflected in these studies, the few studies that conducted the full cradle-grave scope typically found emissions in the post-gate phase to be less than 5% (Iribarren et al. 2010). It's therefore unlikely that the selection of cradle-gate studies will significantly impact on final estimates.

Of the 38 ISSCAAP categories, only 13 contained species with published LCA GHG factors. Many of these species had multiple published studies; in these cases, the mean value of referenced studies was calculated and applied as its emission factor. For the remaining 25 categories for which there are no published LCA data, emission factors were estimated based on species production and morphological similarity to those with published emission factors. The emissions factors applied for all 38 categories are detailed in Supplementary Table 2.

Total global emissions were therefore estimated by year extending from 1950-2013 by multiplying these emissions factors by FAO categorised production data, as shown in (Equation 1).

FAO production datasets can be categorised by species, and/or country of produce. Breakdown by ISSCAAP species category species and country of production were therefore derived using the same methodology as above.

The level of uncertainty within aquaculture estimates is challenging to quantify. Here we have applied a ±27% error range based on observed variance in the intensity of production within a single species, and potential statistical uncertainties in reported FAO production data. Previous studies have suggested—based on analysis of LCA results--that the likely variability in EF for a single species is typically ±15% depending on production systems and practices (Farmery et al. 2015; Baruthio, A. et al. 2015). This variability occurs as a result of differences in production practices, in addition to differences in fish feed compositions, and the CO_2-intensity of energy inputs (which will vary depending on the electricity mix of the country of produce). These uncertainties are therefore reflected in this ±15% error range.

Concern has previously been raised over the accuracy of FAO production statistics (Garibaldi, 2012)—this is in part due to the lack of standardised and consistent reporting from a number of FAO member states, but may also be influenced by newness of aquaculture statistical collection at a global level (Campbell & Pauly, 2013). The FAO is transparent and open about the potential for statistical uncertainty in its production datasets (FAO, 2016), however, it provides no quantified value for the level of error this may introduce in further analyses. Other studies have attempted to scrutinize FAO results by comparison with additional higher-resolution datasets (Campbell & Pauly, 2013). Despite focusing on the narrower scope of global mariculture (aquaculture production within brackish and marine waters), datasets—created from a combination of raw production statistics, spatial Geographical Information System (GIS) components, and rule-based systematic estimation—show strong correlation with reported FAO data. Within these analyses, more than 80% of species' production data had a discrepancy of 5% or less between the global datasets. Although this study did not cover freshwater aquaculture production, we feel this serves as a reasonable estimate for the potential uncertainty in FAO production data. In light of the exclusion of freshwater production however, we have applied a conservative factor of ±10% for production uncertainties.

Our applied error range of ±27% is therefore based on the propagation of EF and production data uncertainty (±15% and ±10%, respectively). The combined error is derived based on independent variable propagation, given by Equation 2:

$$\Delta GHG = \sqrt{(\Delta EF)^2 + (\Delta Q)^2}$$

We acknowledge that further uncertainty is introduced through extrapolation of EF figures between species. However, with present data coverage, this is challenging to quantify. The key research gaps which must be addressed for more robust estimates are discussed in section 4.2. The applied uncertainty ranges within this study should therefore be considered conservative.

It should also be noted that this study (and the LCAs it draws from) covers only emissions related to the farming and production elements of aquaculture. Additional impacts on blue carbon ecosystems, such as mangroves, seagrass and salt marshes, have been noted as a result of coastal degradation—aquaculture has been suggested as one of its many contributing anthropogenic drivers (Ahmed et al. 2016). The attribution of aquaculture to this loss of blue carbon is challenging to quantify and has therefore not been included. The potential contribution of aquaculture to restoring blue carbon and so-called "greening" approaches are included in our discussion.

2.2 Estimating future aquaculture emission projections

Data availability for use in projections of global aquaculture is very limited, making rigorous scenario analysis through to 2030 challenging. In this study we have based mapped scenarios around aquaculture production projections from two core reports: the FAO Fish Model (FAO, 2014), and "Fish to 2030" IMPACT model by the World Bank (World Bank, 2013).

These models incorporate a range of complex social, environmental and economic interactions within their analyses, providing the most comprehensive evaluations of aquaculture projections to date. Both consider a range of scenarios based on supply and demand influences such as climatic impacts on capture fisheries, market dynamics, consumer demand and environmental resource constraints. In this study we have included the World Bank's baseline, low and high growth scenarios; due to the similarity in scenarios between the two sources, only the baseline projection of the FAO Fish Model has been included here.

World Bank projections are based on extrapolation of historical datasets extending only to 2009. Its baseline scenario assumes global annual growth rates drop to 4% by 2010 (i.e. growing at only 4% per annum in the 2010-2020 period). The FAO Fish Model predicts a similar drop in annual growth rates as a result of scarcity in freshwater and suitable farming location availability, and a relative increase in the price of fishmeal, and other feeds (FAO, 2014).

However, updated FAO FishStat datasets have shown that, in the years 2009-2013, annual growth rates have remained high at an average of 7-8%. In previous work "Fish to 2020", the IMPACT model made projections for aquaculture growth during the period 1997-2020 (Delgado et al. 2003).

Assessments of the quality of the model with actual production for the first decade (1997-2007) showed it to underestimate aquaculture growth trends by approximately 100%; the model predicted annual growth rates of only 3.4% relative to the actual 7% average) (World Bank, 2013).

We therefore suggest that, based on more recent data, the World Bank projections could underestimate likely growth through to 2020—possibly by as much as 100%. In recognition of this previous underestimate, and to ensure a fuller range of plausible scenarios, we have additionally included our own "updated" projections. These updated scenarios are provided as a reflection of current growth rate patterns (in line with an 8% initial growth rate rather than its applied 4%), and apply annual growth rates double that of World Bank projections for each of its baseline, 'high' and 'low' growth scenarios.

The applied annual growth rates (%year^{-1}) by decade for each scenario are detailed in Table 1. Note that the FAO Fish Model projections only extend to 2022; here, we have maintained its projected annual growth rate through to 2030.

Scenario	**2010-20**	**2020-30**
World Bank Baseline Growth	4%	2%
Updated Baseline Growth	8%	4%
World Bank High Growth	6%	3%
Updated High Growth	12%	6%
World Bank Low Growth	2%	1%
Updated Low Growth	4%	2%
FAO Fish Model Baseline	2.5%	2.5%

Table 1: Applied annual growth rates for scenario analysis (%year^{-1}). Detailed are the applied annual growth rates of global aquaculture production by decade for each of the mapped scenarios. Applied annual growth rates for our updated scenarios are double that of World Bank projections in line with more recent FAO production datasets.

Future emission projections will be influenced by both global production, as well as the emissions intensity trends. Emissions intensity will be largely determined by the relative growth rates of different species (i.e. if growth rates of species with high EF were stronger relative to lower EF species, we would expect larger increases in global emissions), in addition to changes in the efficiency of farming practices. Both of these variables have been factored into FAO and World Bank production scenarios. Projections anticipate the relative growth rates of key aquaculture species such as tilapia, carp and shrimp to remain approximately similar to historical trends, meaning the weighted EF of production is assumed to be comparable to recent figures. Improvements in the efficiency of farming practices—and feed compositions in particular—have been taken into account through its assumptions on improvements in feed conversion ratios (FCRs) across species.

3. Results

3.1 Global aquaculture emissions—current and historic trends

We estimate that global GHG emissions resulting from aquaculture in 2013 (the latest available FAO dataset) were 227±61 $MtCO_2e$. If measured relative to total emissions from the livestock sector (latest estimates of 7.1 $GtCO_2e$ per annum) (FAO, 2013), aquaculture would account for approximately 3-4%. Considering total aquatic food production provides 17% of global protein demand, of which half is produced from aquaculture (FAO, 2014), our estimates are indicative of aquaculture production having a low carbon-intensity (per unit of protein) relative to other animal-based products.

Estimated global GHG emissions from aquaculture, in line with production trends, demonstrate rapid expansion over the 1950-2013 period (increasing from 2.0±0.5 $MtCO_2e$ in 1950) (Figure 1). Average annual rates of emissions growth per decade are given in Table 2; despite small changes in growth rates per decade, estimated emissions show a largely consistent growth of approximately 8% per annum.

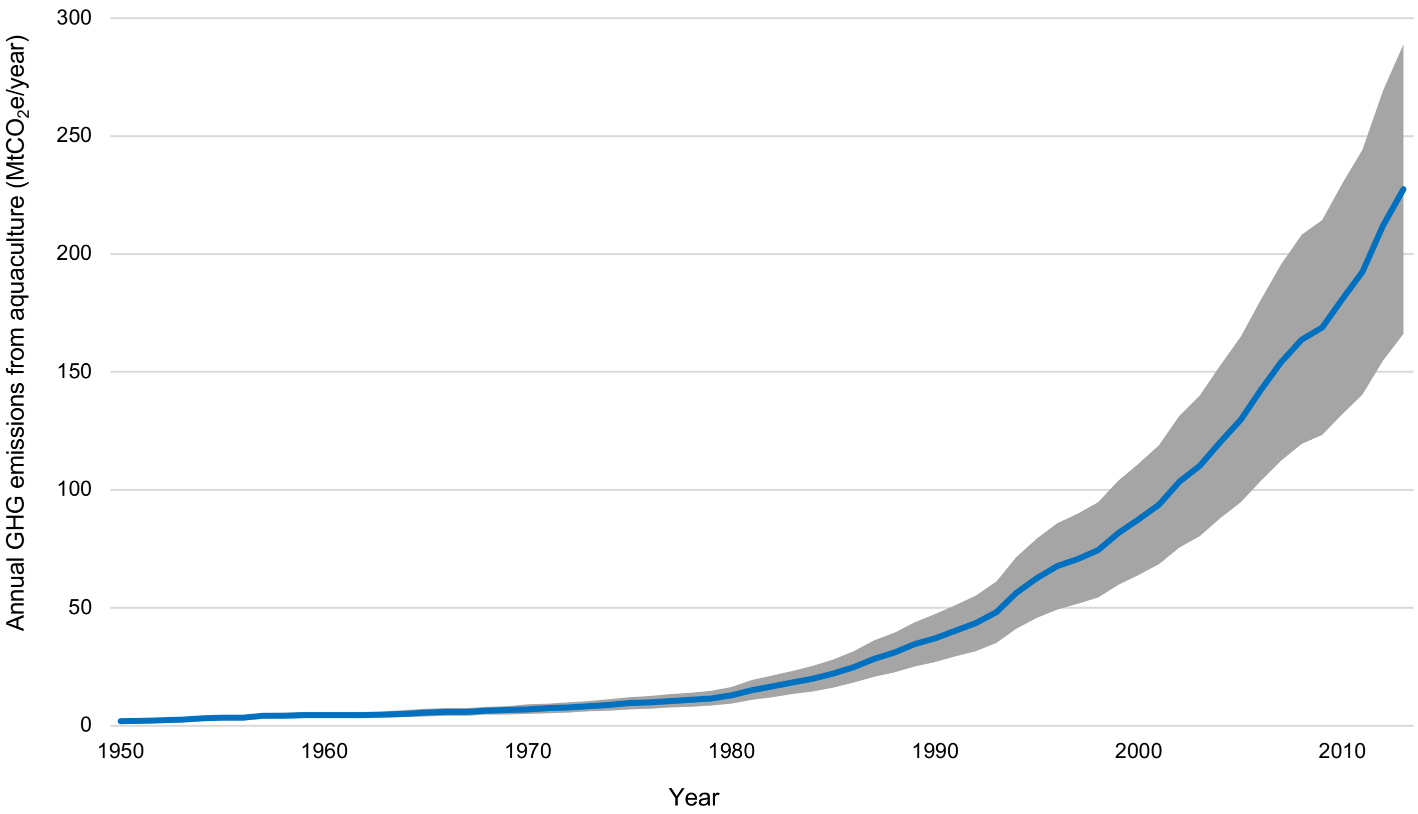

Figure 1: Historic and current global greenhouse gas emissions from aquaculture. Estimated annual global greenhouse gas (GHG) emissions (MtCO2e/year) resulting from aquaculture over the period 1950-2013, based on a combination of FAO production data and species-specific life-cycle analysis (LCA) studies. The shaded area represents an estimated degree of uncertainty of ±27%.

Decade	Average annual growth rate (%year^{-1})
1950-60	9%
1960-70	4%
1970-80	6%
1980-90	11%
1990-00	9%
2000-10	8%
2010-13	8%

Table 2: Greenhouse gas emission growth rates (%year^{-1}) by decade. Average annual global greenhouse gas emission growth rates (%year^{-1}) from aquaculture by decade, based on FAO production data and life-cycle analysis (LCA) studies over the 1950-2013 period.

3.2 Emissions breakdown by aquaculture species

When broken down by species, we observe strong dominance of a few groupings: more than 90% of estimated 2013 emissions can be accounted for from only 10 of the 38 ISSCAAP categories (Table 3). Global GHG emissions are largely dominated by production of carp/cyprinids (52.47MtCO_2e), shrimp (18.68MtCO_2e), tilapia (9.45MtCO_2e), salmon (7.49MtCO_2e), and crustaceans (8.19MtCO_2e), in addition to the broad categories of miscellaneous freshwater, diadromous and coastal fishes (76.52MtCO_2e, 11.99MtCO_2e, and 11.57MtCO_2e respectively). The lack of specification within these latter categories introduces a significant degree of uncertainty in these estimations.

Species (ISSCAAP group)	2013 GHG emissions ($MtCO_2e$)	Percentage of global aquaculture emissions (%)
Miscellaneous freshwater fishes	76.52	34%
Carps, barbels and other cyprinids	52.47	23%
Shrimps, prawns	18.68	8%
Miscellaneous diadromous fishes	11.99	5%
Miscellaneous coastal fishes	11.57	5%
Tilapias and other cichlids	9.45	4%
Freshwater crustaceans	8.19	4%
Salmons, trouts, smelts	7.49	3%
Clams, cockles, arkshells	6.61	3%
Oysters	6.34	3%
Other Species	18.18	8%

Table 3: Breakdown of global greenhouse gas emissions from aquaculture in 2013, by ISSCAAP species category. Estimates show a strong dominance from 10 species groupings (of a total of 28), which account for 92% of global emissions between them.

3.3 Emissions breakdown by country of produce

We observe similar dominance when emissions are aggregated by country of production (Table 4). In line with seafood production data (Cao et al. 2015) as the world's largest producer, China dominates estimated global aquaculture GHG emissions at 57%. The importance of the aquaculture industry in the Asia-Pacific region more widely is apparent with 84% of global GHG emissions produced from only seven Asian nations.

Country of Produce	GHG Emissions from Aquaculture ($MtCO_2e$)	Percentage of global aquaculture emissions (%)
China	119.95	53%
Indonesia	22.48	10%
Vietnam	20.29	9%
India	12.52	6%
Bangladesh	6.56	3%
Philippines	5.29	2%
Thailand	4.21	2%
Egypt	3.55	2%
Norway	2.95	1%
Brazil	2.45	1%
Other Countries	27.22	12%

Table 4: Breakdown of global greenhouse gas emissions from aquaculture in 2013, by country of produce. As reflected in volumetric production figures, China is the world's dominant producer with 57% of total emissions. More than 80% of global emissions arise from only seven nations within the Asia-Pacific region, reflecting a strong dependence on the seafood industry for food and economic security.

3.4 Future aquaculture emission projections

The range of projected future emission scenarios are shown in Figure 2, with final emissions estimates for the year 2030 given in Table 5.

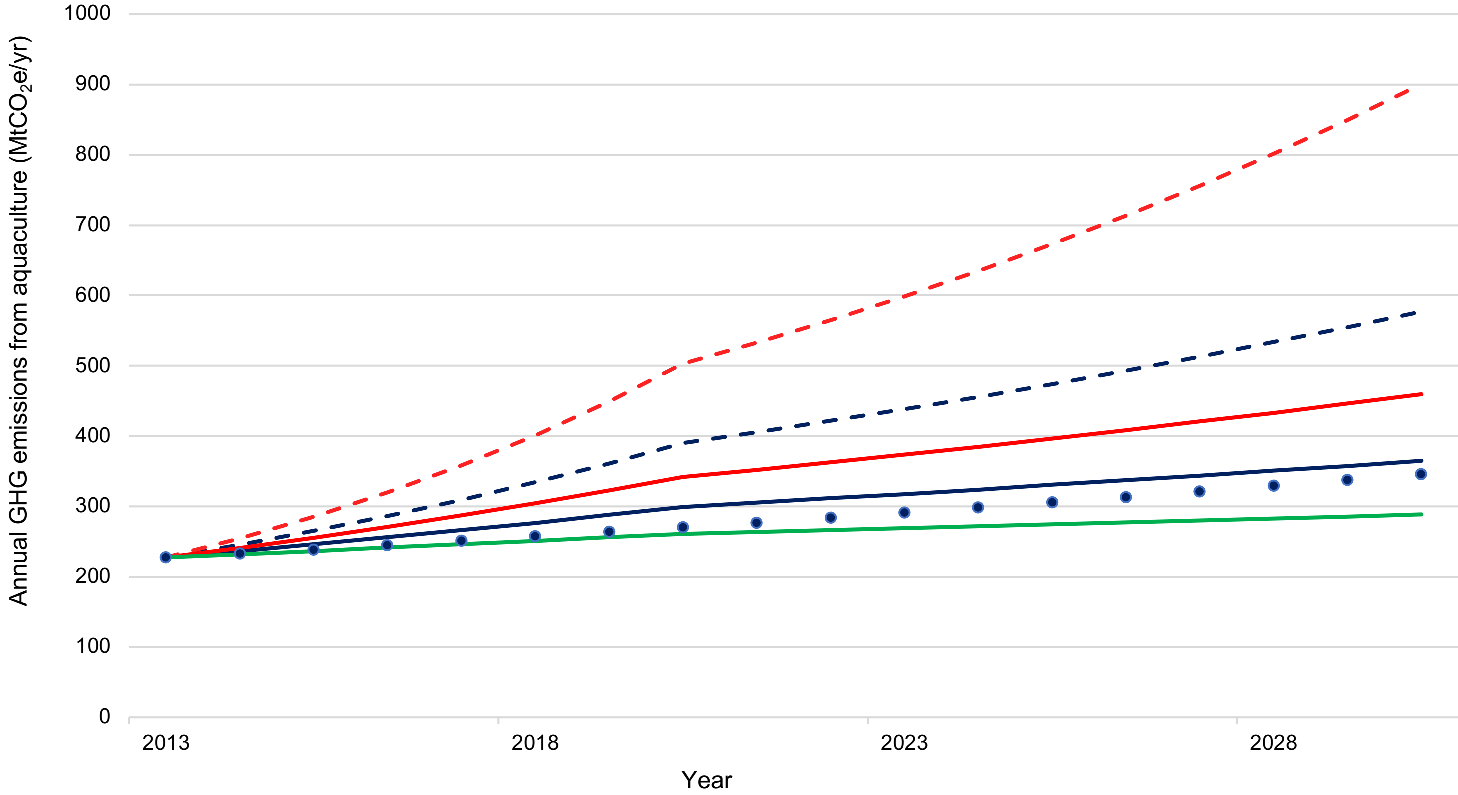

Figure 2: Future projected emissions from aquaculture. Mapped projections of potential future emissions from aquaculture to 2030. World Bank baseline (blue), high (red) and low (green) scenarios are represented as solid lines. Our updated scenarios (BAU in dashed blue; and high growth in dashed red) have assumed a 100% higher growth rate than World Bank figures based on updated FAO data trends. The FAO Fish Model baseline scenario has been included as a blue dotted trend for comparison. Note our updated Low growth curve has not been shown as it directly overlaps with the World Bank baseline scenario.

Scenario	Estimated 2030 Emissions (MtCO$_2$e/y)
World Bank Baseline Growth	365±99
Updated Baseline Growth	577±155
World Bank High Growth	460±124
Updated High Growth	901±243
World Bank Low Growth	289±78
Updated Low Growth	365±99
FAO Fish Model Baseline	346±93

Table 5: Projected emissions (MtCO$_2$e per annum) in 2030 for each scenario pathway.

The World Bank's BAU scenario project global aquaculture GHG emissions could increase to 365±99 MtCO$_2$e by 2030—an approximate 60% increase in emissions from 2013 levels.

Our 'Updated BAU' scenario results in emissions of 577±156 MtCO$_2$e by 2030. As a maximum, our 'Updated High Growth' scenario estimates emissions could potentially reach 900±243 MtCO$_2$e by 2030—an approximate four-fold increase in emissions over the next few decades.

4. Discussion

4.1 Implications for aquaculture as a protein source

Despite the level of uncertainty in these estimates, there are several key discussion and conclusion points which emerge. As it stands, global aquaculture, if included within total livestock emissions would add an additional 3-4% to this sector (FAO, 2013). Even in the case that our estimates are conservative, we can still conclude with confidence that this source is unlikely to exceed more than 5-10% relative to current livestock emissions. Breakdown of these emissions shows a clear dominance from a few species groupings (carp, tilapia, shrimp, salmon and miscellaneous categories) and countries of produce (China, Indonesia, Vietnam, India, Bangladesh, Philippines). It's expected that future growth will continue to be focused within these nations and will be dominated by a few key species groupings: carps, tilapia and shrimp, in particular (World Bank, 2013; Cao et al. 2015). This has important implications for the focus of any mitigation efforts, efficient production systems and community capacity-building.

Our mapped projections of how aquaculture emissions could evolve suggest that these are likely to, at a minimum, grow by 50% by 2030 based on World Bank estimates. We suggest that future emissions growth could extend well beyond this, dependent on a range of factors. This future trajectory will be largely determined by a complex combination of consumer demand drivers; species selection; production systems and shifts towards/away from intensification; and importantly feed quantity and composition. Although FAO and World Bank have attempted to factor these variables into their production scenarios, improved and continued understanding of these interactions will prove crucial in enhanced projections and mitigation strategies.

The dominance of fisheries, and subsequently the expansion of aquaculture in South Asia has both geographical, social and economic drivers. The distribution of coastal waters, low-lying deltas and floodplains make fish production and catch an obvious choice for food supply in several countries; Bangladesh for example, has one hectare of water for every 20 people (WorldFish, 2009). Increasing population and natural resource pressures in the region mean aquaculture plays a key role in rural food security (FAO, 2016) .However, its role within international markets is also growing, with the export of high-value seafood products bringing important economic growth to national economies in the region (WorldFish, 2009).

Fish products are some of the most-traded food commodities worldwide (Farmery et al. 2015), and the growing dependence of aquaculture not only for food, but also economic security - especially within the Asia-Pacific region – is an important consideration alongside environmental impacts when informing policy and recommendations. Shrimp, for example, is a widely-traded, high-value commodity and provides a key source of income for a number of aquaculture farmers (FAO, 2016). However, shrimp has a comparatively high emissions intensity and low conversion efficiency relative to alternative seafood species such as tilapia and salmon (Pelletier & Tyedmers, 2007)—this raises a complex challenge of how to balance recommendations for species selection with emissions mitigation and economic security.

Beyond total and species-specific volumetric demands, the GHG emissions-intensity of production systems will be a major determinant of the sustainability of protein provision through global aquaculture. GHG intensity incorporates a number of considerations, including the intensification of production methods, development of best practice approaches, and importantly the evolving quantities and composition of aquaculture feed.

4.2 Mitigation potential

Aquaculture environments can be complex, with GHG-intensity and mitigation potential determined by country of produce, geographical constraints and choice of production system. There has been a general trend towards the intensification of aquaculture, with the replacement of extensive systems for those with higher unit production (Diana, 2009). Despite a lack of published work on comparisons of different production systems (extensive, semi-intensive and intensive), the limited available data suggest that more intensive systems may also produce higher emissions per unit fish (Cao et al. 2011; 2013; Iribarren et al. 2010). This is largely a result of higher nutrient, feed and electricity inputs required for more intensive systems. Higher emissions intensities are also found for inland recirculating systems relative to marine-based aquaculture systems, as a result of the increased energy requirements for water aeration and quality maintenance (Ayer & Tyedmers, 2009; Pelletier & Tyedmers, 2010). As a result, future emission trajectories will be a function of trends towards system intensification, and the ratio of inland-to-offshore farms.

A complete quantification of global mitigation potential is challenging to estimate without adequate LCA data coverage of a range of production systems and practices across most farmed products. However, we have attempted to quantify the mitigation potential which may be achieved for a single species category, thereby exemplifying the scale of mitigation which may be attainable across the sector.

As a specific case, we have selected shrimp production systems; shrimp farming systems can cover a range of GHG-intensities depending on practice and geographical location, from 910kgCO_2e/ton in organic practices (Mungkung et al. 2006) through to 5910kgCO_2e/tonne in intensive systems (Cao et al. 2013). The carbon impacts of intensive shrimp farming extends beyond its cradle-to-gate footprint—important losses of mangrove forest ecosystems (and thereby the loss of key carbon sinks) has been noted as a result of the ecosystem disruption created from shrimp farming systems (Ahmed et al. 2016). In this case, the transition towards less-intensive, or even organic, systems may be considered particularly effective in mitigating both carbon and ecosystem impacts. We estimate that the mitigation potential of global shrimp farming, if all systems were managed organically (thereby reducing its EF to 910kgCO_2e/kg), would have been up to 14.7MtCO_2e in 2013, and by 2030 could total as much as 46.3MtCO_2e per year. This represents a saving of up to 79% for shrimp species.

It is challenging to extrapolate such results for estimation of mitigation potential for other aquaculture species. While organic systems have been shown to be significantly less carbon-intensive relative to intensive systems for shrimp species, LCA studies have shown that such assumptions cannot be assumed across all species—in some cases of salmon farming, organic practices showed no reduction in GHG emissions relative to conventional methods (Pelletier & Tyedmers 2007). The potential for mitigation, and the selection of appropriate practices to maximise benefits, is therefore largely species- and geographically-dependent. Broad recommendations for how to reduce environmental impact are therefore difficult to provide. Aquaculture practices and methods are continually evolving through technological knowledge innovation (Diana et al. 2013)—while the general trend is towards intensification, this continuous evolution provides an ideal opportunity for research on mitigation practices to feed into this process. To maximise effectiveness, this should be evaluated at the local and species level.

One of the promising evolutions in practice has been the adoption of Integrated Multi-Trophic Aquaculture (IMTA) in a number of countries. IMTA is the farming of finfish, shellfish and seaweed in a multi-trophic environment such that an efficient recycling of nutrients can occur between species (Ahmed et al. 2016). IMTA practices have been shown to not only promote a more environmentally friendly means of aquaculture production, but also provide a more positive social and economic return for local populations through the production of additional valued products (Ahmed & Toufique 2015). In attempting to simultaneously improve environmental and social sustainability, such systems may provide a preferred approach. It is useful to contextualise the level of mitigation potential which might exist in the development of such systems globally. Previous estimates of the carbon sequestration potential of IMTA in the form of mangrove, shellfish and seaweed systems (assuming a 25% restoration and yield increase) are approximately 0.5MtC per year (Ahmed et al. 2016)—combined this would total 1.5MtC (5.5MtCO_2e) per year. Relative to estimated annual emissions in 2013 of 227MtCO_2e, and potential increases to 901MtCO_2e by 2030, the mitigation potential of this practice (even in the case that restoration and yields of shellfish and seaweed species were multiple times that assumed in the previous study). While our results suggest that the potential carbon savings of IMTA are likely to be small relative to total sectoral emissions, the additional environmental and economic benefits of such practices should not be underestimated.

It's well-documented within the literature that, for most aquaculture species, the production of fish feed is a dominant source of GHG emissions (Cao et al. 2015; Pelletier et al. 2009). In particular for fishes (such as salmon, tilapia and trout and carp), feed production can be responsible for greater than 90% of total life-cycle emissions, especially for compositions with a high ratio of fish meal (FM) or livestock products in the feed mix (Parker, 2012). Fish typically have a lower feed conversion ratio (FCR) than livestock alternatives (Cao et al. 2013), making aquaculture a comparatively lower-carbon means of animal protein production. An additional emissions advantage is gained through comparison of GHG source for marine farming and terrestrial livestock systems. Whereas feed production tends to be dominant for aquaculture species, enteric fermentation (direct emissions) dominates ruminant production systems (FAO, 2013). These direct ruminant emissions are absent in aquaculture systems—another reason why typical fish protein is lower-carbon than other animal-based sources.

The importance of feed for aquaculture emissions, however, raises important discussion points within the wider context of terrestrial and marine-based farming systems. As the availability of wild fish products for aquaculture feed declines, there is an increasing migration towards crop and livestock-based alternatives (FAO, 2014)—a transition which could have important implications for terrestrial agricultural systems. To this point, aquaculture and land-based production systems have been largely treated separately. However, the expansion of aquaculture demand, as well as the increasing intensification of these systems, will continue to increase pressure on land-based resources (which already face a range of environmental constraints). We therefore suggest that food, and more specifically protein, production systems need to be assessed through a more integrated approach. Through a more holistic evaluation, more optimal solutions for total resource efficiency and GHG mitigation may be achieved.

4.3 Data gaps and research needs

This study provides a first estimate of GHG emissions resulting from global aquaculture. It should be noted that, despite drawing upon the best available data in the published literature, these estimates still carry a large degree of uncertainty as a result of gaps in current knowledge. However, we feel it serves as a useful estimate of the relative magnitude of GHG emissions from this sector, and highlights the key data gaps that need to be addressed in order to improve such estimates.

Of the 38 ISSCAAP species categories, only 13 had published GHG emission factors; the remaining 25 had to be estimated from these based on species similarity. The level of uncertainty this introduced was somewhat reduced by the fact that the dominant aquaculture species (by volume), such as salmon, tilapia, shrimp, and turbot, were those with published EFs. However, an obvious improvement on these estimates could be achieved through establishing GHG EFs for a wider range of key aquaculture species. Of particular importance is the study of carp species—their influence on total GHG emissions is likely to be significant as a result of high production volumes globally (Diana, 2009).

The ISSCAAP categories include several broad miscellaneous or "nei" (not elsewhere included) groupings. It is unlikely that a single EF can be accurately applied to all species in this category. Furthermore, the non-specific and sometimes inaccurate nature of reporting in some major aquaculture areas remains a key difficulty in assessing the true climate change impact of the aquaculture sector (Cao et al. 2015; Garibaldi, 2012). A higher degree of specificity and verification in reporting and categorisation of production would therefore facilitate more accurate assessments.

Finally, a number of different production systems can be applied for aquaculture growth—for a single species, the variability in GHG emissions-intensity of production can typically be ±15%, and sometimes greater (Farmery et al. 2015), depending on the selected production system. Since FAO datasets do not segregate production figures based on production methods, system-specific EFs could not be applied in this study. Better estimates could therefore be achieved if production data were provided at this higher level of resolution. To fully utilise improved resolution production datasets however, LCA analyses would also need to cover the broad spectrum of production systems globally to obtain system-specific EFs.

5. Conclusion

This study has attempted to make a first global estimate of GHG emissions resulting from the aquaculture sector based on currently available data. As such, it should be treated as a starting basis for future estimates to build upon, should wider data availability become available. Results derived from the latest FAO production figures estimate 2013 annual global emissions to be 227±61 $MtCO_2e$. As the fastest growing food sector globally, we expect aquaculture emissions to continue to increase; our business-as-usual and highest growth projections estimate sectorial emissions could reach

577±156 $MtCO_2e$ and 901±243 $MtCO_2e$, respectively, by 2030. This highlights the importance of improving understanding of aquaculture systems—relative efficiencies of different species; production systems and feed types—in order to improve emissions estimates and develop effective mitigation strategies in line with global and national GHG reduction targets.

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Concluding Remarks

There were two overarching objectives of this thesis project. The first of these was to develop a framework by which we can reframe the way we view, understand and ultimately model the capacity of our food systems. This framework was designed to provide a holistic overview of food systems, extending from agricultural production through to final food supply ('field-to-fork'). It additionally attempted to normalise food metrics from standard absolute mass metrics to understandable measures related to daily per capita nutritional values. In this way, food systems can be quantified in relation to their nutritional value and can be modelled across all essential nutritional components.

The ability to model and quantify systems at this level provides multiple insights relating to both malnutrition and food system pathways, as it:

- provides an estimate for total agricultural production (prior to value chain losses)—this develops a sense of maximum system capacity prior to inefficiencies;
- allows for estimation of total food system efficiency: how much of primary food production is finally available for human consumption;
- models the relative contribution and losses across the various stages of the supply chain; this not only gives a sense of where the hotspots where losses are greatest, but also provides a measure of the relative effectiveness of interventions to reduce losses;
- allows for future modelling of food system capacities by allowing for changes with regards to crop yield, livestock efficiency, dietary changes, food loss/waste prevention, and changes in allocation to non-food uses;
- can be replicated and scaled to a range of levels including global, regional, national and sub-national (if data are available);
- can be used to understand and analyse the full nutritional outlook by modelling for any macronutrient, micronutrient or amino acid;
- allows normalising to average daily per capita values, giving a true sense of scale with regard to food security, adequacy and addressing malnutrition.

In this thesis I applied this framework at a global level, with a further focus on India as a national-level example.

Results highlight that at a global level, we produce the equivalent of 5800 kilocalories and 170 grams of protein per person per day through crops alone (see Chapters One and Two). However, major system inefficiencies mean that less than half of crop calories and protein is delivered (or converted) for final food supply. Pathway inefficiencies are even more acute for micronutrients; more than 60% of all essential micronutrients assessed in this study are lost (see Chapter Two). Globally I found very large inequalities in per capita levels of food production, ranging from 19,000 kilocalories (729 grams of protein) per person per day in North America to 3300 kilocalories (80 grams of protein) in Africa. Large variations are also seen in terms of food system efficiency, ranging from 15-20% in North America to 80-90% in Africa (see Chapter One). Understanding regional inefficiencies, inequalities and trade imbalances will be crucial to meet the needs of a growing global population.

The rescaling of this framework to analyse the Indian food system (Chapters Three and Four) highlights the need for this understanding of regional and national food surpluses and deficits, to develop a global food system that works for all. India was selected as an exemplar at the national level for several reasons, including its already prevalent malnutrition challenges; continued population growth in the coming decades; strong domestic reliance on agricultural production; and economically-driven dietary transitions.

The results of my analyses, ranging from present through to 2030 and 2050 projected scenarios highlight that India has limited domestic capacity to meet the needs of its growing population. India's domestic production capacity would result in severe malnutrition across a large proportion (>60%) of the population, even under ambitious yield and waste reduction scenarios in 2030 and 2050. This deficit will have to be addressed through optimised intervention and trade developments. In the absence of a major shift away from its determined self-sufficiency model, India will fail to meet its Sustainable Development Goals (SDG) targets of ending malnutrition.

We therefore see how global, regional and national-level applications of this framework connect: we can effectively model the future capacity of domestic food systems to meet growing demand (by adjusting population metrics, yield values, waste reduction interventions); provide a sense of magnitude for eventual surpluses and deficits, and better understand where such global imbalances lie.

The goal of addressing malnutrition needs to be coupled with enhanced food system efficiencies and reduction of environmental impact. Part One of this thesis highlighted the large inefficiencies which exist within our system pathways: at a global level less than half of crop calories and protein are available or converted for final food supply, with losses of up to 80% in some high-income nations. A major driver of this loss lies in the poor conversion efficiency of livestock. Part Two of this thesis therefore attempted to explore some of the potential solutions to this challenge of providing nutritious, high-quality diets in a more sustainable way.

An important first step in shifting dietary behaviours towards healthy and sustainable habits is ensuring that guidelines and advice are effectively communicated to consumers. Whilst a number of studies have compared the greenhouse gas footprint of different diets, such as meat-eater, vegetarian, Mediterranean and vegan, no studies to date have attempted to quantify the footprint of different national recommended diets. My results in Chapter Five highlighted several important conclusions: firstly, dietary guidelines for most countries fail to recognise or incorporate any sustainability-related considerations to their recommendations; most guidelines were too vague for a consumer to follow specifically, with poor quantification of food group thresholds or limits; the greenhouse gas footprint of most countries which did provide specific guidelines were incompatible with climate targets necessary to keep average global warming below 2°C. In fact, the recommended USA or Australian diet actually increases emissions relative to the business-as-usual diet in 2050. Therefore, whilst we often associate unsustainable diets with overconsumption (which remains the case), healthy, recommended dietary guidelines are also currently incompatible with our sustainability targets.

The final two chapters of this thesis attempted to explore how nutrition and environmental outcomes can be coupled through alternative high-quality protein sources. Meat substitutes, which currently hold a small (but growing) share of the protein market offer multiple health benefits relative to meats, and can also achieve significant greenhouse gas emission reductions. However, current substitute products are comparable in price, or more expensive, than meat proteins limiting consumer uptake in high-income markets and pricing them out of developing markets. Results in my economic scenarios (see Chapter Six) found that meat substitute products have significant health and emission benefits, but are strongly sensitive to both price and consumer acceptability.

The final chapter (Chapter Seven) attempted to fill a notable gap within the literature of our understanding of aquaculture (fish farming) impact. Aquaculture now accounts for more than half of global seafood production, yet its total greenhouse gas emissions are yet to be quantified. This makes it challenging to contextualise whether it provides sustainability benefits over alternative protein products, and how its emissions will change with growing demand (it is currently the fastest growing food sector). My results highlighted the strong dependency of species-type and production system when assessing environmental impact; emissions vary significantly between species and the type of production system in place. Understanding these differences is crucial if aquaculture is to provide a sustainable option to global protein supply; poor choices with regards to species and farming practice could in fact achieve the opposite. This study provided the first quantification of global greenhouse gas emissions, estimated to be 227±61 $MtCO_2e$, with a projected increase to 365±99$MtCO_2e$ by 2030. This was equivalent to approximately 3-4% of total livestock emissions. Since aquaculture is estimate to account for 8-9% of global protein demand, it nonetheless has potential as an efficient protein source if sustainability is incorporated as a key decision-making criterion.

This thesis was not without its limitations. The analysis—particularly with regards to Part One—relied heavily on the UN FAO's Food Balance Sheets. The FAO openly acknowledges that its balance sheets are not perfect: data reporting, availability and accuracy across some countries is insufficient to capture the complete value chain across all commodities. In this case, the FAO relies on field experts to use all available data to interpolate and estimate the complete supply chain (see Supplementary Discussion on Food Balance Sheets). Furthermore, in these analyses I relied on standard nutritional composition factors for food commodities. The use of such factors introduces a clear generalisation: every kilogram of wheat product, for example, will not have an identical nutritional profile.

In addition, the use of metrics normalisation to an average daily per capita availability value introduced a clear simplification, both with regards to actual availability and nutritional requirement. The India-specific analysis attempted to correct for some inequality in availability and requirement through demographic weighting and population distribution curve methods, however even these corrections did not fully address such assumptions.

My India-specific analysis introduced another important limitation: this work focused strongly on a supply-side model of agricultural and food system capacity. This fails to take important consumer, market, pricing and trade feedback into account. These factors have critical implications for the final outcomes of such assessments. Results of the Indian food system analysis suggested widespread and severe malnutrition if modelled within domestic resource limits. However, domestic responses in terms of dietary changes, pricing and international markets will likely buffer some of these severe impacts. This study on agricultural capacity would therefore strongly benefit from incorporation within economic and market analyses to provide a more realistic and accurate view of these complex systems.

As a result of these limitations, this work is not intended, nor do I recommend it, for use in detailed or specific malnutrition intervention programmes. The most commonly used data source for local-level planning and nutritional assessments is household survey data, which more accurately records actual household or individual-level consumption. This remains the best method for assessing malnutrition, and planning necessary for health or nutritional interventions. Nonetheless, household survey data are limited in their ability to provide contextual information on food systems, efficiency, losses and future capacity to deliver for changing food demand. They capture only the final stage of an extensive value chain.

At present, the only available data source for this holistic food system assessment is the FAO's Food Balance Sheets. So, whilst they are imperfect, they are currently the best available source for such analysis. If we were to conclude that our global food balance sheets are inadequate to attempt such analysis, then we must also conclude that we cannot understand our food systems at a very basic and high level.

A clear and important next step must therefore be to develop universal, high-quality coverage of food systems data for all countries. This process of data gathering, quality checks and transparent access will become increasingly important for all nations as we work towards the SDGs by 2030. Despite its limitations, this work draws some clear conclusions about the state of our food systems. It's clear that if we are to couple our ambitions of ending malnutrition and doing this in a sustainable way by 2030, or even 2050, we need a major transformation in how food systems operate. Understanding how they currently do so—and the levers we can utilise to transform them—is critical to achieving this. This thesis attempts to take an important first—but incomplete—step in getting us there.

Supplementary Material

Chapter One:

Feeding the world: a 50-year analysis of regional and national food system efficiency

Full supplementary data detailing all output results for all countries and regions based on caloric and protein production; trade-adjusted domestic availability; self-sufficiency ratio; and system 'efficiency' for every year from 1965- 2013 is available upon request.

This data is provided as a Supplementary Text File within Chapter One's submission for academic publication.

Chapter Two:

Beyond calories: a holistic assessment of the global food system

Supplementary Tables

	Infants	Children				Men		Women					
	0-12 months	1-3 years	4-6 years	7-9 years	10-18 years	19-65 years	65+ years	10-18 years	19-50 years	51-65 years	65+ years	Pregnancy	Lactation
% population	3.7%	5.4%	5.3%	6.8%	7.0%	28.3%	3.3%	6.6%	19.1%	6.4%	4.2%	1.9%	1.9%
Weighted for pop >1 year	0.00%	5.6%	5.5%	7.1%	7.3%	29.4%	3.5%	6.8%	19.9%	6.7%	4.3%	2.0%	2.0%

Supplementary Table 1: Global population gender and age demographics. Percentages of the global population within each age and gender grouping[1]. This study excludes infants <1 year old, hence percentages have also been normalised to those >1 year, to give a total percentage of 100%.

	Men						Women						
	1-3 years	**4-6 years**	**7-9 years**	**10-18 years**	**19-65 years**	**65+ years**	**10-18 years**	**19-50 years**	**51-65 years**	**65+ years**	**Pregnancy**	**Lactation**	**Weighted EAR**
Isoleucine (mg/g protein)	31	31	30	30	30	30	30	30	30	30	30	30	**30.1**
Leucine (mg/g protein)	63	61	60	60	59	59	60	59	59	59	59	59	**59.5**
Lysine (mg/g protein)	52	48	48	47	45	45	47	45	45	45	45	45	**46.1**
Methionine +Cysteine (mg/g protein)	26	24	23	23	22	22	23	22	22	22	22	22	**22.5**
Phenylalanine +Tyrosine (mg/g protein)	46	41	41	40	38	38	40	38	38	38	38	38	**39.1**
Threonine (mg/g protein)	27	25	25	24	23	23	24	23	23	23	23	23	**23.6**
Tryptophan (mg/g protein)	7.4	6.6	6.5	6.3	6	6	6.3	6	6	6	6	6	**6.2**
Valine (mg/g protein)	42	40	40	40	39	39	40	39	39	39	39	39	**39.4**
Histidine (mg/g protein)	18	16	16	16	15	15	16	15	15	15	15	15	**15.4**

Supplementary Table 2: Daily Estimated Average Requirements (EAR) of essential amino acids. Estimated Average Requirements (EAR) of all essential amino acids (AA) by age and gender demographics. Weighted EAR values for the population are derived from global population distribution figures in Supplementary Table 1.

	Children			Men			Women						
	1-3 years	4-6 years	7-9 years	10-18 years	19-65 years	65+ years	10-18 years	19-50 years	51-65 years	65+ years	Preg	Lact	Weighted EAR
Iron absorption assumed (%)	5	5	5	5	5	5	5	8	8	8	8	8	
Iron (mg/day)	6.4	9.3	11.4	22.9	13.1	13.1	16.9	13.1	13.1	13.1	29.2	17.9	**13.8**
Calcium (mg/day)	500	800	800	1100	800	1100	1100	800	1100	1100	1000	1000	**877**
Zinc (mg/day)	2.5	4	7	8.5	9.4	9.4	7.3	6.8	6.8	6.8	10.5	10.9	**9.6**
Vitamin A (µg/day)	286	321	357	429	429	429	429	357	357	429	571	607	**397**
Vitamin B_6 (mg/day)	0.4	0.5	0.8	1.1	1.1	1.4	1	1.1	1.1	1.3	1.6	1.7	**1.0**
Vitamin B_{12} (µg/day)	0.7	1	1.5	2	2	2	1.5	2	2	2	2.2	2.4	**1.8**
Folate (mg/day)	120	160	250	330	320	320	250	330	320	320	520	450	**299**
Vitamin C (mg/day)	13	22	22	63	75	75	56	60	60	60	70	100	**58.4**

Supplementary Table 3: Daily Estimated Average Requirements (EAR) of key dietary vitamins and minerals. Estimated Average Requirements (EAR) of key vitamins and minerals by age and gender demographics. Weighted EAR values for the population are derived from global population distribution figures in Supplementary Table 1.

Europe (inc. Russia)	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	2%	4%	0.5%, 10%	2%	25%
Roots and tubers	20%	9%	15%	7%	17%
Oilseeds and pulses	10%	1%	5%	1%	4%
Fruits and vegetables	20%	5%	2%	10%	19%
Meat	3.1%	0.7%	5%	4%	11%
Fish and seafood	9.4%	0.5%	6%	9%	11%
Milk	3.5%	0.5%	1.2%	0.5%	7%

North America and Oceania	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	2%	2%	0.5%, 10%	2%	27%
Roots and tubers	20%	10%	15%	7%	30%
Oilseeds and pulses	12%	0%	5%	1%	4%
Fruits and vegetables	20%	4%	2%	12%	28%
Meat	3.5%	1.0%	5%	4%	11%
Fish and seafood	12%	0.5%	6%	9%	33%
Milk	3.5%	0.5%	1.2%	0.5%	15%

Sub-Saharan Africa	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	6%	8%	3.5%	2%	1%
Roots and tubers	14%	18%	15%	5%	2%
Oilseeds and pulses	12%	8%	8%	2%	1%
Fruits and vegetables	10%	9%	25%	17%	5%
Meat	15%	0.7%	5%	7%	2%
Fish and seafood	5.7%	6%	9%	15%	2%
Milk	6%	11%	0.1%	10%	0.1%

North Africa, West and Central Asia	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	6%	8%	2%, 7%	4%	12%
Roots and tubers	6%	10%	12%	4%	6%
Oilseeds and pulses	15%	6%	8%	2%	2%
Fruits and vegetables	17%	10%	20%	15%	12%
Meat	6.6%	0.2%	5%	5%	8%
Fish and seafood	6.6%	5%	9%	10%	4%
Milk	3.5%	6%	2%	8%	2%

South and Southeast Asia	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	6%	7%	3.5%	2%	3%
Roots and tubers	6%	19%	10%	11%	3%
Oilseeds and pulses	7%	12%	8%	2%	1%
Fruits and vegetables	15%	9%	25%	10%	7%
Meat	5.1%	0.3%	5%	7%	4%
Fish and seafood	8.2%	6%	9%	15%	2%
Milk	3.5%	6%	2%	10%	1%

Latin America	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	6%	4%	2%, 7%	4%	10%
Roots and tubers	14%	14%	12%	3%	4%
Oilseeds and pulses	6%	3%	8%	2%	2%
Fruits and vegetables	20%	10%	20%	12%	10%
Meat	5.3%	1.1%	5%	5%	6%
Fish and seafood	5.7%	5%	9%	10%	4%
Milk	3.5%	6%	2%	8%	4%

Supplementary Table 4: Loss and waste percentages by food chain stage and commodity group by region. Due to poor data availability on food loss figures at the national level, regional average figures from the FAO (FAO 2011b) were applied to derive estimates of macronutrient losses at each stage in the global commodity chain.

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Chapter Three:

Sustainable Food Security in India – Domestic Production and Macronutrient Needs

Supplementary Tables

	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	6%	7%	3.5%	2%	3%
Roots and tubers	6%	19%	10%	11%	3%
Oilseeds and pulses	7%	12%	8%	2%	1%
Fruits and vegetables	15%	9%	25%	10%	7%
Meat	5.1%	0.3%	5%	7%	4%
Fish and seafood	8.2%	6%	9%	15%	2%
Milk	3.5%	6%	2%	10%	1%

Supplementary Table 1: Loss and waste percentages by food chain stage and commodity group for South and Southeast Asia. Due to poor data availability on India-specific food loss figures, regional average figures from the FAO (FAO 2011) were applied to derive estimates of macronutrient losses at each stage in the Indian commodity chain.

Scenario	Assumptions
2011 Baseline Scenario	- Production, imports, exports, stocks, seed, feed, and non-food uses from FAO Food Balance Sheets (http://faostat.fao.org/beta/en/#home). - Production, postharvest, processing, distribution and household waste percentage figures by commodity type from FAO (2011) Global food losses and food waste – Extent, causes and prevention. These factors are provided in Table S3. - Nutritional composition factors based on global average used in FAO Food Balance Sheet Handbook. - 2011 population figures based on UN Population Prospects of 1.2474 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).
2030 Baseline Scenario	- Yield (and food production) stagnates at 2011 levels. - 2030 population figures based on UN Population Prospects of 1.5276 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).
Scenario 1 (2030): Halving food losses	- Percentage losses from production, postharvest, processing and distribution were halved their values in baseline scenario. - Yield (and food production) stagnates at 2011 levels. - 2030 population figures based on UN Population Prospects of 1.5276 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).
Scenario 2 (2030): achieving 50% attainable yields (AY)	- Yields for all commodities assumed 50% of their India-specific attainable yield value from Mueller et al. (2012). - Loss and waste percentages assumed the same as in baseline scenario. - 2030 population figures based on UN Population Prospects of 1.5276 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).
Scenario 3 (2030): achieving 75% attainable yields (AY)	- Yields for all commodities assumed 75% of their India-specific attainable yield value from Mueller et al. (2012). - Loss and waste percentages assumed the same as in baseline scenario. These factors are provided in Table S3. - 2030 population figures based on UN Population Prospects of 1.5276 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).
2050 Baseline Scenario	- Average per capita meat demand increases to 18.3kg and milk to 110 kilograms based on FAO projections (Alexandratos & Bruinsma, 2012). This comprises 3.5kg of bovine meat, 1.2kg mutton & goat meat; 1kg pigmeat; 12.5kg poultry; and 0.8kg other meats). Assumes increased feed

	demand is met on the basis of increased crop allocation rather than pasture in line with livestock-specific protein conversion efficiencies from Herrero et al. (2013). - Climatic impacts on yields is assumed based on literature review of impacts in the result of a doubling in pre-industrial CO_2 levels. Yield impacts are summarised in table S4. - 2050 population figures based on UN Population Prospects of 1.62 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).
Scenario 1 (2050): Halving food losses	- Percentage losses from production, postharvest, processing and distribution were halved their values in baseline scenario. - Average per capita meat demand increases to 18.3kg and milk to 110 kilograms based on FAO projections (Alexandratos & Bruinsma, 2012). This comprises 3.5kg of bovine meat, 1.2kg mutton & goat meat; 1kg pigmeat; 12.5kg poultry; and 0.8kg other meats). Assumes increased feed demand is met on the basis of increased crop allocation rather than pasture in line with livestock-specific protein conversion efficiencies from Herrero et al. (2013). - Climatic impacts on yields is assumed based on literature review of impacts in the result of a doubling in pre-industrial CO_2 levels. Yield impacts are summarised in table S4. - 2050 population figures based on UN Population Prospects of 1.62 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).
Scenario 2 (2050): achieving 75% attainable yields (AY)	- Yields for all commodities assumed 75% of their India-specific attainable yield value from Mueller et al. (2012). These are combined with climatic impacts on yields is assumed based on literature review of impacts in the result of a doubling in pre-industrial CO_2 levels. Yield impacts are summarised in table S4. - Average per capita meat demand increases to 18.3kg and milk to 110 kilograms based on FAO projections (Alexandratos & Bruinsma, 2012). This comprises 3.5kg of bovine meat, 1.2kg mutton & goat meat; 1kg pigmeat; 12.5kg poultry; and 0.8kg other meats). Assumes increased feed demand is met on the basis of increased crop allocation rather than pasture in line with livestock-specific protein conversion efficiencies from Herrero et al. (2013). - Loss and waste percentages assumed the same as in baseline scenario. These factors are provided in Table S3. - 2050 population figures based on UN Population Prospects of 1.62 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).
Scenario 3 (2050): achieving 90% attainable yields (AY)	- Yields for all commodities assumed 90% of their India-specific attainable yield value from Mueller et al. (2012). These are combined with climatic impacts on yields is assumed based on literature review of impacts in the result

	of a doubling in pre-industrial CO_2 levels. Yield impacts are summarised in table S4. - Average per capita meat demand increases to 18.3kg and milk to 110 kilograms based on FAO projections (Alexandratos & Bruinsma, 2012). This comprises 3.5kg of bovine meat, 1.2kg mutton & goat meat; 1kg pigmeat; 12.5kg poultry; and 0.8kg other meats). Assumes increased feed demand is met on the basis of increased crop allocation rather than pasture in line with livestock-specific protein conversion efficiencies from Herrero et al. (2013). - Loss and waste percentages assumed the same as in baseline scenario. These factors are provided in Table S3. - 2050 population figures based on UN Population Prospects of 1.62 billion. - Coefficient variation in caloric, protein and fat of 0.26 based on log-normal distribution from FAO (2014).

Supplementary Table 2: Assumptions and sources for figures used within all scenarios from 2011 baseline to 2050 scenarios.

Crop	2000 yield (tha-1)	2011 yield (tha-1)	50% AY (tha-1)	Percentage increase from 2011 to 50% AY	75% AY (tha-1)	Percentage increase from 2011 to 75% AY	90% AY (tha-1)	Percentage increase from 2011 to 90% AY
Barley	0.79	2.35	2.59	10%	3.88	65%	4.66	97.6%
Cassava	25.63	36.48	27.08	0%	28.89	0%	30.46	0.0%
Groundnut	0.97	1.31	1.02	0%	1.18	0%	1.32	0.7%
Maize	1.54	2.48	1.97	0%	2.64	7%	3.11	25.5%
Millet	0.79	1.19	0.88	0%	1.06	0%	1.2	1.2%
Potato	18.41	22.72	18.85	0%	20.35	0%	21.46	0.00%
Rapeseed	0.94	1.26	0.98	0%	1.08	0%	1.19	0.00%
Rice	2.95	3.59	3.19	0%	3.82	6%	4.33	20.7%
Rye	1.72	1.72	1.78	3%	2.39	39%	2.87	66.9%
Sorghum	0.78	0.95	0.94	0%	1.19	25%	1.39	46.5%
Soybean	0.93	1.20	1.06	0%	1.41	18%	1.67	39.2%
Sugarbeet	36.18	36.18	38.07	5%	48.43	34%	57.48	58.9%
Sugarcane	66.53	69.25	69.68	1%	76.29	10%	85.82	23.9%
Sunflower Seed	0.49	0.71	0.69	0%	0.96	36%	1.13	59.6%
Wheat	2.76	2.99	3.08	3%	3.63	21%	4.07	36.2%

Supplementary Table 3: Indian baseline and attainable yield (AY) values for key crop types. Year 2000 and all attainable yield values have been derived from Mueller et. al (2012)(Mueller et al. 2012), and 2011 yield data derived from the FAOstats database (http://faostat.fao.org/beta/en/#home). The necessary percentage increase in yield from 2011 levels to reach each of the AY values has also been shown.

Crop	Estimated impact of climate change on yield in 2050
Rice	-7.4%
Wheat	-12.0%
Coarse Cereals	-12.0%
Sorghum	-12.0%
Millet	-4.3%
Maize	-2.5%
Pulses	-12.0%
Chickpeas	-12.0%
Peas	-12.0%
Lentils	-12.0%
Oilseeds	0.5%
Groundnuts	-23.0%
Soybean	-18%
Sugarcane	-10%
Potato	-22%

Supplementary Table 4: Average estimated climatic impacts on Indian crop yields in 2050. Average values have been assumed based on the range of historic studies on yield sensitivities and climatic models within literature review (Mall et al. 2006). These models are projected on the basis of a doubling of CO_2 from pre-industrial (which is approximately equivalent to a business-as-usual scenario).

Supplementary Discussion

Supplementary Discussion on FAO Food Balance Sheets (FBS)

The challenge in developing accurate Food Balance Sheets (FBS) at the national and global level are widely acknowledged and discussed by the FAO (FAO 2001). The accuracy of FBS is constrained by the completeness and reliability of commodity production and utilization statistics in national records.

The high prevalence of small-holder and subsistence farms in India makes estimates of total production challenging—in this case, completeness of data collection as well as the reliability of farmer reports (farmers often equate production with tax collection) introduce uncertainty to final estimates. Such uncertainty is also present in values of non-food utilizations. Import and export data—which is more meticulously recorded—is likely to be the most accurate of the national statistics recorded in FBS. Issues in agricultural and nutritional data collection in India are described in detail within the FAO's 2030/50 Agricultural Outlook (Alexandratos & Bruinsma 2012).

Food loss and waste figures, especially in countries where small-holder farms and local markets are prevalent, has a high level of uncertainty. To our knowledge, national statistics on supply chain losses and waste in India is not available down to the level of commodity and chain stage breakdown. For this reason, published FAO figures on regional losses for South and Southeast Asia were applied in this study (Supplementary Table 1). This introduces further uncertainty to supply chain losses.

Where data within FBS is deemed to be incomplete or inconsistent, judgement from national expert opinion and technical expertise within the FAO is used to provide as reflective coverage as possible. While likely to provide a close approximation, this is rarely 100% accurate.

Nonetheless, the FBS is currently the best available data source for construction and analysis of complete commodity chain analysis. Literature is available based on studies conducted at the household level, however, very few studies attempt to provide coverage of the food chain dynamics from crop production through to human consumption. Without a complete overview of the commodity chain, the impacts of interventions (such as improved food management and storage;

trade; reduced allocation of crops to non-food uses; improved crop yields) are almost impossible to assess.

As the FAO notes, food balance sheets "provide an approximate picture of the overall food situation in a country and can be useful for economic and nutritional studies, for preparing development plans and for formulating related projects" (FAO 2001). In this study, we have therefore relied on FAO datasets in order to construct a high-level overview of the Indian commodity chain to assess its overall capacity to meet the country's growing nutritional demands at present, in the near-, and long-term. This overview will not be perfect in a statistical sense, however its strong correlation (<5-10% discrepancy) with national household surveys gives confidence that it provides a good approximation of the national food outlook. For its utilisation in this analysis—to inform broad policy focus and assess the potential of supply chain interventions—we therefore deem it to be appropriate.

Improved agricultural, food waste and nutritional reporting would allow for more accurate and reliable estimates to be constructed. Such data collection will provide important in informing future policy and allowing for forward planning in this sector. It should therefore be an important area of focus for India in the coming years.

Supplementary Discussion on Attainable Yields (AY)

Our scenarios to 2050 are therefore modelled on the basis of closure of the yield gap to 75% and 90% AY. To assess whether these estimates were realistic, necessary growth rates were cross-checked based on historical yield growth rates in India.

Wheat yields in India are growing at approximately 0.9% per annum (non-compounding) from 2009 levels—farm yields (FY) and have shown roughly linear growth at this rate over the last decade (Fischer et al. 2014). To attain 90% AY figures used in this study, yields would have to increase by 36% from 2011 levels, equating to a consistent annual growth rate of 0.9-1.0% to 2050. In other words, India would have to maintain its historic growth rates to 2050 to reach this level. Rice yields have been increasing at an annual non-compounding rate of 1.0-1.1% (Fischer et al. 2014). The yield gap to 90% AY (based on figures used in this study) for rice is smaller than for wheat, at 21% from 2011 levels; this converts to a 0.5-0.6% annual growth rate to 2050. India would therefore not need to maintain its consistent historic growth rate of 1.0-1.1% to reach this level.

While 90% AY figures may be achievable based on historic growth rates, it's important to acknowledge that this improvement would have to be maintained over a further 30-40 years. This raises key concerns given water scarcity and soil fertility constraints. The Green Revolution in India allowed it to achieve impressive increases in agricultural output, primarily through improved nutrient management and irrigation networks. Declining water tables are already a primary concern in India (Mekonnen & Hoekstra 2016)—ever-increasing irrigation demands to maintain historic growth rates are unlikely to be sustained to 2050. Further concern over yield stagnation globally —in wheat, rice and maize in particular—has been raised in recent years (Ray et al. 2012). Therefore while estimates vary on levels of attainable yield, figures referenced in this study for maximum 90% AY scenarios are assumed to be potentially realistic but highly ambitious. Note that this study is based on traditional crop varieties and has not included potential genetic variation and modification varieties, which are currently not consented in India (with the exception of Bt Cotton).

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Chapter Four:

Quantifying and Addressing India's Hidden Hunger

Supplementary Tables

	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	6%	7%	3.5%	2%	3%
Roots and tubers	6%	19%	10%	11%	3%
Oilseeds and pulses	7%	12%	8%	2%	1%
Fruits and vegetables	15%	9%	25%	10%	7%
Meat	5.1%	0.3%	5%	7%	4%
Fish and seafood	8.2%	6%	9%	15%	2%
Milk	3.5%	6%	2%	10%	1%

Supplementary Table 1: Loss and waste percentages by food chain stage and commodity group for South and Southeast Asia. Due to poor data availability on India-specific food loss figures, regional average figures from the FAO (FAO 2011b) were applied to derive estimates of macronutrient losses at each stage in the Indian commodity chain.

	Infants		Children			Men				Women			
	0-12 months	1-3 years	4-6 years	7-9 years	10-18 years	19-65 years	65+ years	10-18 years	19-50 years	51-65 years	65+ years	Pregnancy	Lactation
Percentage of population	3%	8%	5%	5%	9%	30%	2%	8%	16%	5%	3%	2%	4%
Weighted for population >1 year	0%	8%	5%	5%	9%	31%	2%	8%	16%	5%	3%	2%	4%

Supplementary Table 2: Indian population gender and age demographics. Percentages of the Indian population within each age and gender grouping (Mark et al. 2016). This study excludes infants <1 year old, hence percentages have also been normalised to those >1 year, to give a total percentage of 100%.

	Children			Men			Women						
	1-3 years	**4-6 years**	**7-9 years**	**10-18 years**	**19-65 years**	**65+ years**	**10-18 years**	**19-50 years**	**51-65 years**	**65+ years**	**Pregnancy**	**Lactation**	**Weighted EAR**
Iron absorption assumed (%)	5	5	5	5	5	5	5	8	8	8	8	8	
Iron (mg/day)	6.4	9.3	11.4	22.9	13.1	13.1	16.9	13.1	13.1	13.1	29.2	17.9	**14.0**
Calcium (mg/day)	417	458	583	833	625	667	833	625	667	667	667	625	**639**
Zinc (mg/day)	-	-	-	-	-	-	-	-	-	-	-	-	**6.9**
Vitamin A (µg/day)	286	321	357	429	429	429	429	357	357	429	571	607	**403**
Vitamin B_6 (mg/day)	1.25	1.25	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	**1.2**
Vitamin B_{12} (µg/day)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	**1.2**
Folate (mg/day)	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	**1.25**

Supplementary Table 3: Daily Estimated Average Requirements (EAR) of key dietary vitamins and minerals. Estimated Average Requirements (EAR) of key vitamins and minerals by age and gender demographics (World Health Organization 2005). Weighted EAR values for the population are derived from Indian population distribution figures in Supplementary Table 2.

	Infants	Children			Men			Women						
	0-12 months	1-3 years	4-6 years	7-9 years	10-18 years	19-65 years	65+ years	10-18 years	19-50 years	51-65 years	65+ years	Pregnancy	Lactation	Weighted EAR
Isoleucine (mg/g protein)	-	31	31	30	30	30	30	30	30	30	30	30	30	**30**
Leucine (mg/g protein)	-	63	61	60	60	59	59	60	59	59	59	59	59	**60**
Lysine (mg/g protein)	-	52	48	48	47	45	45	47	45	45	45	45	45	**46**
Methionine +Cysteine (mg/g protein)	-	26	24	23	23	22	22	23	22	22	22	22	22	**23**
Phenylalanine +Tyrosine (mg/g protein)	-	46	41	41	40	38	38	40	38	38	38	38	38	**39**
Threonine (mg/g protein)	-	27	25	25	24	23	23	24	23	23	23	23	23	**24**
Tryptophan (mg/g protein)	-	7.4	6.6	6.5	6.3	6	6	6.3	6	6	6	6	6	**6.2**
Valine (mg/g protein)	-	42	40	40	40	39	39	40	39	39	39	39	39	**40**
Histidine (mg/g protein)	-	18	16	16	16	15	15	16	15	15	15	15	15	**16**

Supplementary Table 4: Daily Estimated Average Requirements (EAR) of essential amino acids. Estimated Average Requirements (EAR) of all essential amino acids (AA) by age and gender demographics (FAO 2011a). Weighted EAR values for the population are derived from Indian population distribution figures in Supplementary Table 2.

Crop	2000 yield (tha^{-1})	2011 yield (tha^{-1})	90% AY (tha^{-1})	Percentage increase from 2011 to 90% AY
Barley	0.79	2.35	4.66	97.6%
Cassava	25.63	36.48	30.46	0.0%
Groundnut	0.97	1.31	1.32	0.7%
Maize	1.54	2.48	3.11	25.5%
Millet	0.79	1.19	1.2	1.2%
Potato	18.41	22.72	21.46	0.00%
Rapeseed	0.94	1.26	1.19	0.00%
Rice	2.95	3.59	4.33	20.7%
Rye	1.72	1.72	2.87	66.9%
Sorghum	0.78	0.95	1.39	46.5%
Soybean	0.93	1.20	1.67	39.2%
Sugarbeet	36.18	36.18	57.48	58.9%
Sugarcane	66.53	69.25	85.82	23.9%
Sunflower Seed	0.49	0.71	1.13	59.6%
Wheat	2.76	2.99	4.07	36.2%

Supplementary Table 5: Indian baseline and 90% attainable yield (AY) values for key crop types. Year 2000 and 90% attainable yield (Mueller et al. 2012), and 2011 yield data derived from the FAOstats database (http://faostat.fao.org/beta/en/#home). The necessary percentage increase in yield from 2011 levels to reach the 90% AY value has also been shown.

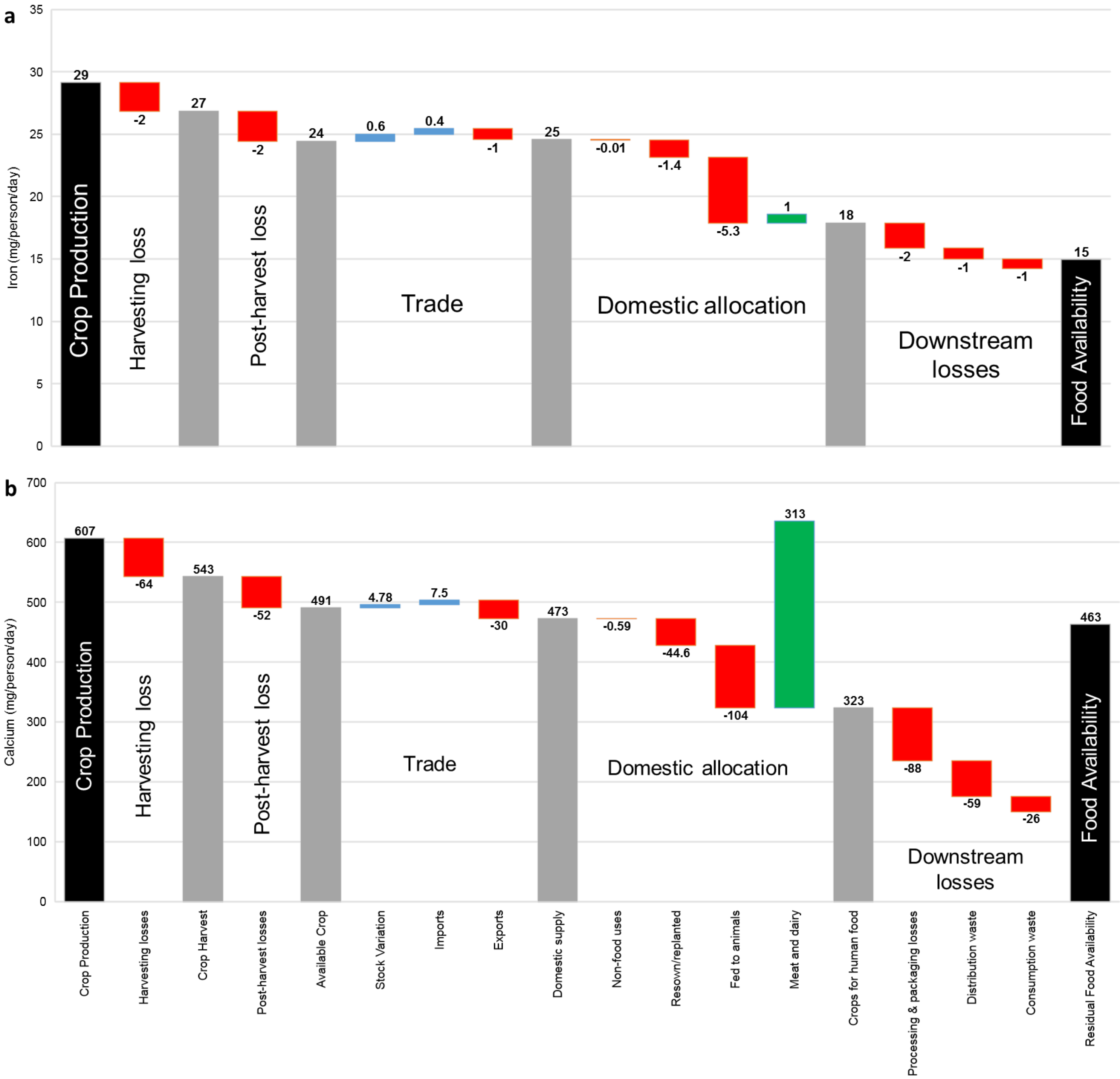
Crop	Estimated impact of climate change on yield in 2050
Rice	-7.4%
Wheat	-12.0%
Coarse Cereals	-12.0%
Sorghum	-12.0%
Millet	-4.3%
Maize	-2.5%
Pulses	-12.0%
Chickpeas	-12.0%
Peas	-12.0%
Lentils	-12.0%
Oilseeds	0.5%
Groundnuts	-23.0%
Soybean	-18%
Sugarcane	-10%
Potato	-22%

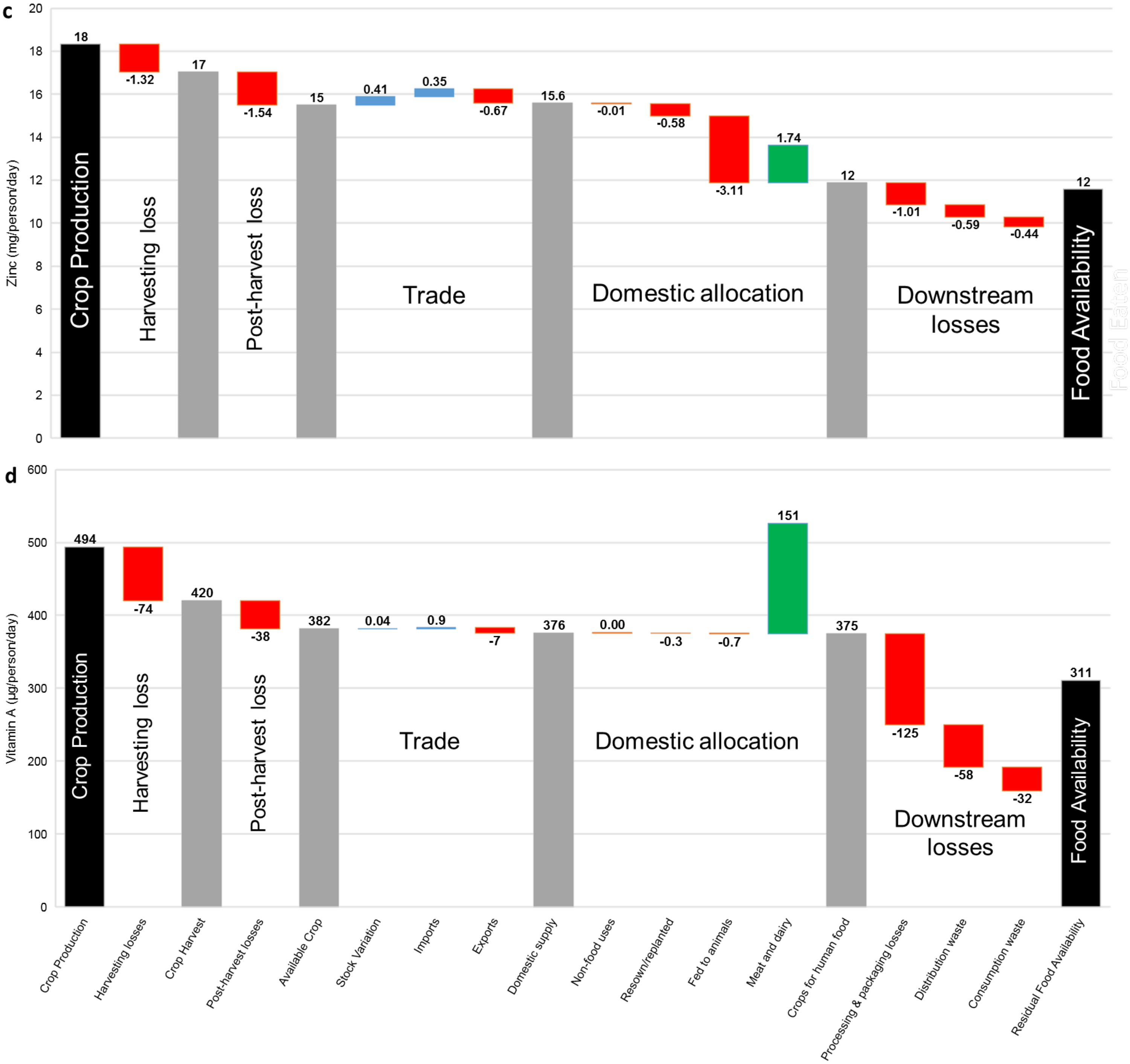
Supplementary Table 6: Average estimated climatic impacts on Indian crop yields in 2050. Average values have been assumed based on the range of historic studies on yield sensitivities and climatic models within literature review (Mall et al. 2006). These models are projected on the basis of a doubling of CO_2 from pre-industrial (which is approximately equivalent to a business-as-usual scenario).

	Calcium (Ca)	Iron (Fe)	Zinc (Zn)	Vitamin A	Vitamin B6 and B12	Iodine (I)	Folate (Fol)	Lysine (Lys)
Cereals								
Starchy roots and tubers								
Nuts, seeds and oilcrops								
Pulses and legumes								
Fruit								
Vegetables								
Milk and dairy products								
Eggs								
Red meats								
White meats								
Fish and seafood								

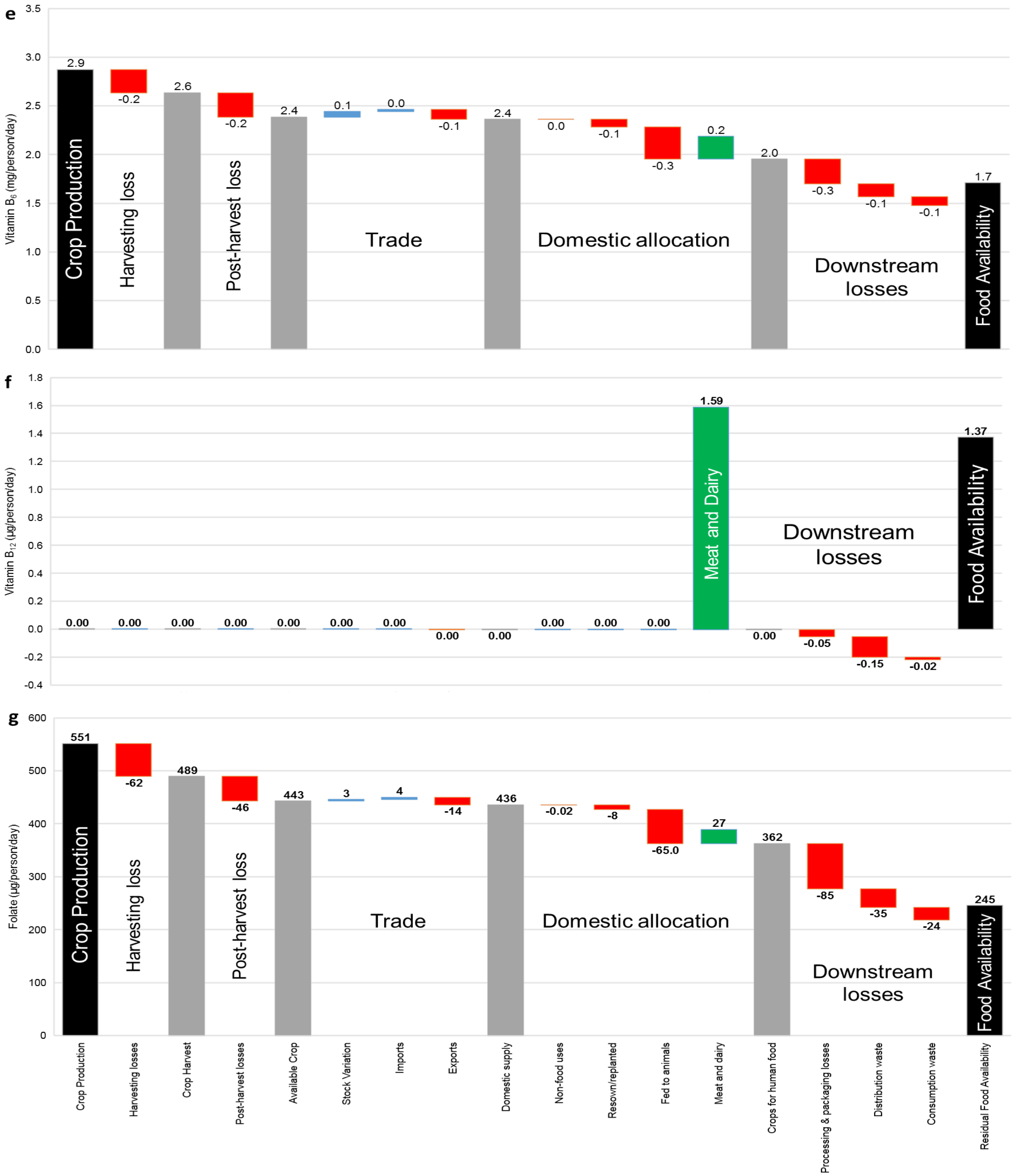
Supplementary Table 7: Dietary sources of micronutrients by commodity group. Key dietary sources of key vitamins, minerals, and limiting amino acid, lysine have been highlighted in grey.

Supplementary Figures





c
Zinc (mg/person/day)
0
2
4
6
8
10
12
14
16
18
20
18
-1.32
17
-1.54
15
0.41
0.35
-0.67
15.6
-0.01
-0.58
-3.11
1.74
12
-1.01
-0.59
-0.44
12
Crop Production
Harvesting loss
Post-harvest loss
Trade
Domestic allocation
Downstream losses
Food Availability
d
Vitamin A (µg/person/day)
0
100
200
300
400
500
600
494
-74
420
-38
382
0.04
0.9
-7
376
0.00
-0.3
-0.7
151
375
-125
-58
-32
311
Crop Production
Harvesting loss
Post-harvest loss
Trade
Domestic allocation
Downstream losses
Food Availability
Crop Production
Harvesting losses
Crop Harvest
Post-harvest losses
Available Crop
Stock Variation
Imports
Exports
Domestic supply
Non-food uses
Resown/replanted
Fed to animals
Meat and dairy
Crops for human food
Processing & packaging losses
Distribution waste
Consumption waste
Residual Food Availability



Supplementary Figures 1a-g: Production and losses in the Indian food system from 'field to fork' in 2011. Food pathways in (a) iron; (b) calcium; (c) zinc; (d) vitamin A; (e) vitamin B6; (f) vitamin B12; and (g) folate, from crop production to food eaten, normalised to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate micronutrient availability at intermediate stages of the chain.

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Chapter Five:
Impacts of global dietary guidelines on climate change

Supplementary Tables

	Staples	Pulses	Fish	Dairy	Eggs	Poultry	Oils	Sugar	Fruit & Veg	Red Meat
WHO Healthy	391	16	30	260	26	50	43	45	492	33
India (vegetarian)	560	90	0	300	0	0	30	30	400	0
India (non-vegetarian)	560	90	10	300	0	20	30	30	400	0
Germany	550	0	27	350	28	35	30	50	650	35
China	650	150	75	300	50	35	30	50	850	35
Canada	560	50	21	500	32	38	30	50	640	38
Australia	550	50	30	625	38	38	29	50	750	38
USA	550	20	32	690	38	38	29	50	600	38

Supplementary Table 1: Recommended intakes for the average diet in WHO and national dietary guidelines in grams per day ($gday^{-1}$) across the range of food commodity groups.

	Staples	Pulses	Fish	Dairy	Eggs	Poultry	Oils	Sugar	Fruit & Veg	Red Meat
United Kingdom	nq	nq	24	250	nq	nq	nq	nq	400	nq
South Africa	nq	nq	35	450	28	45	nq	nq	400	45
Japan	500	nq	225	500	nq	35	nq	nq	640	35
Nigeria	nq	nq	nq	nq	nq	nq	nq	nq	nq	nq
Seychelles	nq	45	57	750	nq	nq	nq	nq	400	nq

Supplementary Table 2: Recommended intakes for the average diet across a range of national dietary guidelines measured in grams per day ($gday^{-1}$) across the range of food commodity groups. Such guidelines are deemed insufficient to provide clear, actionable guidance. "nq" stands for "non-quantifiable" and highlights commodities within the guidelines for which a quantified recommendation cannot be given.

Food Commodity Group	Average GHG intensity ($kgCO_2ekg^{-1}$)
Sugar	1.32
Roots	0.02
Pulses	0.1
Maize	0.18
Wheat	0.32
Fruits	0.36
Rice	0.64
Vegetables	0.64
Oils	16.31
Eggs	1.4
Poultry	6.82
Pork	8.0
Dairy	2.42
Beef	43.25
Fish	7.8

Supplementary Table 3: Average greenhouse gas (GHG) emissions intensity of agricultural production across a range of commodity groups. Figures are adopted from (Tilman & Clark 2014) based on life-cycle analysis (LCA) meta-analyses. Note that these LCAs are defined by a cradle-to-farmgate boundary scope.

Supplementary References

Tilman, D. & Clark, M., 2014. Global diets link environmental sustainability and human health. *Nature*, 515(7528), pp.518–522. Available at: http://www.nature.com/nature/journal/v515/n7528/full/nature13959.html.

Chapter Six:
Global potential of meat substitutes for climate change mitigation and improved human health

Supplementary Health Methods

Health methods were based on a similar methodology to that applied in by Springmann et al. in "Mitigation potential and global health impacts from emissions pricing of food commodities" (Springmann, Mason-D'Croz, Robinson, Wiebe, et al. 2016).

Number of deaths avoided as a result of diet- and weight-related factors were calculated based on population attributable fractions (PAFs), which characterises the number of disease-attributed deaths avoided when the level of risk exposure transitioned from business-as-usual conditions to those in each of the mapped scenarios. PAFs were calculated using Eq. (A.1):

$$PAF = \frac{\int RR(x)P(x)dx - \int RR(x)P'(x)dx}{\int RR(x)P(x)dx} \qquad \text{Eq. (A.1)}$$

where:

RR(x) = relative risk of disease for a given risk factor level x

P(x) = number of people in the population with a risk factor level x in the business-as-usual scenario

P'(x) = number of people in the population with a risk factor level x in the mapped reduction scenario

Three key risk factors were considered in this study: the burden of coronary heart disease (CHD), stroke and cancers related to excessive meat consumption—each of these carry a level risk dependent on diet-related factors (i.e. level of meat, and red meat intake), and weight-related factors (risk factor based on being clinically overweight or obese). The total PAF (PAFtot) is therefore given as the combined sum of these independent risk factors (PAFi) in Eq. (A.2).

$PAFtot = 1 - \prod_i (1 - PAFi)$ Eq. (A.2)

To convert this change in risk exposure to number of avoided deaths, independent PAF values were multiplied by their disease-specific death rates (DR) and the number of individuals within a population (P) as in Eq. (A.3):

$\Delta deaths\ (i) = PAF(i).\ DR(i)\ .P$ Eq. (A.3)

Since disease death rates vary by demographic, population (P) figures were differentiated based on age group and country; and death rates (DR) by age group, and disease. DR values were acquired from the Global Disease Burden project, which defines death rates across 235 mortality causes and 20 age groups (Lozano et al. 2012).

Diet-related risk factors

Diet-related risk factors (RR) were based on several assumptions: that the total population was subject to the risk associated with its regional consumption level, c; that risk begin increasing above zero meat intake levels; and these risks have no upper limit. In this assessment, the assumed serving size, s, of meat was taken to be 100g. The risk factor for a given country was therefore defined by Eq. (A.4):

$RRi = RR^{\frac{c}{s}}$ Eq. (A.4)

This yields a PAF calculation defined by Eq. (A.5):

$PAFi = 1 - \frac{RR^{\frac{c(scn)}{s}}}{RR^{\frac{c(ref)}{s}}}$ Eq. (A.5)

Where c(ref) denotes the consumption level in business-as-usual assumptions, and c(scn) is the level of consumption under meat substitution scenarios.

Weight-related risk factors

This analysis considered the number of deaths avoided as a result of a reduction in weight-related disease burden as a result of a reduction in BMI through meat substitution. The relationship between national average BMI and caloric intake was established based on global datasets from the FAO and

WHO for the years 1980-2009 (Springmann, Mason-D'Croz, Robinson, Garnett, et al. 2016). This yields the polynomial relationship, Eq (A.6):

$$BMI(r) = (-9.53.10^{-7}).kcal(r)^2 + (7.87.10^{-3}).kcal(r) + 10.18 \quad \text{Eq. (A.6)}$$

Where kcal(r) denotes the average daily caloric consumption in a given country and BMI(r) its average BMI value.

Caloric intake and resultant BMI values by country were retrieved from FAO databases (FAO n.d.), and BMI adjustments in each scenario made based on the change in caloric intake (using nutritional composition values in Table A2) which would occur from the relevant level of meat substitution.

This combined FAO and WHO database also allowed for the calculation of the relationship between average BMI in a given country with the prevalence of overweight individuals (%) (Eq. (A.7)); and the prevalence of obese individuals (%) (Eq. (A.8)). This relationship yielded the following relationships, with an R^2 value of 0.73 and 0.97 respectively:

$$\%\ \text{overweight} = (0.0006.BMI(r)^2) + (0.0003.BMI(r)) - 0.0747 \quad \text{Eq. (A.7)}$$

$$\%\ \text{obese} = (0.0045.BMI(r)^2) - (0.1755.BMI(r)) - 1.7356 \quad \text{Eq. (A.8)}$$

For each risk category, PAFs were then calculated by Eq. (A.9):

$$PAFw = RRw.PPw.P \quad \text{Eq. (A.9)}$$

Where PPw is the percentage of the population in the overweight-obese or obese categorisation; and P is the individuals in a given population.

Changes in mortality

To derive the number of premature deaths avoided, Δdeaths was calculated independently for each of the risk factors, then combined to given the total number of deaths avoided (Eq. (A.10)):

$$\Delta deaths\ (i,w) = PAF(i,w)\ .\ DR\ .P \quad \text{Eq. (A.10)}$$

Relative Risk Factors

The relative risk factors (RR) used for calculation of PAF values by disease were derived based on pooled analyses of cohort studies (Prospective Studies Collaboration et al. 2009) and meta-analysis of cohort and case-control studies (Micha et al. 2010; Chen et al. 2013; World Cancer Research Fund & American Institute for Cancer Research 2007) utilised in Springmann et al.'s "Mitigation potential and global health impacts from emissions pricing of food commodities" (Springmann, Mason-D'Croz, Robinson, Wiebe, et al. 2016). The RR factors applied in this analysis are summarised in Supplementary Table 4.

Supplementary Tables

Country	2020 Population (thousands)	Average per capita consumption ($kgyear^{-1}$) Beef	Pig	Poultry	Sheep
Australia	25598	22.1	20.6	43.5	7.1
Canada	37600	17.5	16.8	35.1	0.9
Israel	8718	20.4	1.5	57.6	1.8
Japan	125039	6.8	15.2	13.9	0.1
New Zealand	4730	13.9	18.1	39.5	2.2
Russian Federation	142898	11.5	21.4	27.9	1.2
South Africa	56669	10.7	3.4	32.9	3.1
USA	333546	25.5	23.4	49.4	0.3
Norway	5494	16.4	23.9	23.9	4.8
Switzerland	8654	20.9	29.1	16.3	1.4
Iceland	342	17.4	4.96	17.0	8.1
Ukraine	43679	7.1	14.9	25.9	0.4
EU28	507889	10.8	32.6	23.5	1.8

Supplementary Table 1: Population and estimated 2020 meat consumption patterns within the 40 countries included in this analysis. Population figures have been attained from the UN Population Division (United Nations 2015) and meat consumption projections from the OECD-FAO Agricultural Outlook (OECD 2016) for 2020.

Per 100g product	Beef	Pork	Poultry	Lamb	Quorn™ Mycoprotein
Calories (kcal)	150	326	122	263	85
Protein (g)	18.5	11	12.3	13.5	11
Fat (g)	7.9	31	7.7	22.8	3

Supplementary Table 2: Nutritional composition of average meat commodities and Quorn™ mycoprotein products. Nutritional composition of meat commodities was assumed based on reported values in the FAO's Food Balance Sheets (FBS) (FAO 2001) and mycoprotein based on nutritional and sustainability assessments (Finnigan 2010).

	Beef	Pork	Poultry	Lamb	Quorn™ Mycoprotein
GHG intensity ($kgCO_2ekg^{-1}$ product)	53.05	6.08	5.76	25.58	5.6

Supplementary Table 3: Greenhouse gas (GHG) intensity of commodity production. Average GHG intensity ($kgCO_2ekg^{-1}$) of meat and substitute production based on life-cycle analysis (LCA). Meat intensities were assumed based on global average values from FAO full value chain assessments (Gerber et al. 2013), and Quorn™ mycoprotein based on comparable LCA methodologies (Finnigan 2010; Smetana et al. 2015).

Risk factor	CHD	Stroke	Cancer
Meat consumption	1.25	1.1	1.16
Overweight	1.31	1.07	1.1
Obese	1.78	1.55	1.4

Supplementary Table 4: Relative Risk (RR) parameters for coronary heart disease (CHD), stroke and cancer (forms related to meat consumption and obesity) by factor.

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Chapter Seven:

Global greenhouse gas emissions from aquaculture

Supplementary Tables

Species (Common) Name	Country of Study	LCA Methodology	GWP ($kgCO_2e/ton$)	Production System	Year of Study	Reference
Arctic char	Canada	Attributional	28200	Recirculating tank	2009	(Ayer & Tyedmers 2009)
Striped catfish	Vietnam	Attributional	8930	Flow-through pond	2009	(Bosma et al. 2009)
Cod	Norway	Attributional	2900	-	2009	(Winther et al. 2009)
Haddock	Norway	Attributional	3300	-	2009	(Winther et al. 2009)
Herring	Norway	Attributional	520	-	2009	(Winther et al. 2009)
Mackerel	Norway	Attributional	540	-	2009	(Winther et al. 2009)
Atlantic Salmon	Canada	Attributional	2073	Marine net-pen	2009	(Ayer & Tyedmers 2009)
Atlantic Salmon	Canada	Attributional	1900	Marine floating bag	2009	(Ayer & Tyedmers 2009)
Atlantic Salmon	Canada	Attributional	2770	Saltwater flow-through	2009	(Ayer & Tyedmers 2009)
Atlantic Salmon	UK	Attributional	3270	Intensive	2009	(Pelletier et al. 2009)
Atlantic Salmon	UK	Attributional	2150	Marine cages	2011	(Boissy et al. 2011)
Atlantic Salmon	UK	Attributional	2480	Marine cages	2011	(Boissy et al. 2011)
Atlantic Salmon	Norway	Attributional	3000	Intensive	2009	(Ellingsen et al. 2009)
Atlantic Salmon	Norway	Attributional	2900	-	2009	(Winther et al. 2009)
Atlantic Salmon	Canada	Attributional	2370	Intensive	2009	(Pelletier et al. 2009)
Atlantic Salmon	Chile	Attributional	2300	Intensive	2009	(Pelletier et al. 2009)
Atlantic Salmon	Norway	Attributional	1790	Intensive	2009	(Pelletier et al. 2009)
Sea bass	Greece	Attributional	3600	Sea cage	2009	(Aubin et al. 2009)
Sea bass	Tunisia	Attributional	11087	Flow-through	2011	(Jerbi et al. 2012)
Sea bass	Tunisia	Attributional	17449	Flow-through	2011	(Jerbi et al. 2012)
Shrimp (Tiger Prawn)	USA	Attributional	5910	Intensive	2009	(Cao et al. 2013)
Shrimp (White-leg)	China	Attributional	5280	Intensive	2011	(Cao et al. 2011)
Shrimp (White-leg)	China	Attributional	2750	Semi-intensive	2011	(Cao et al. 2011)

Shrimp (Tiger Prawn)	Thailand	Attributional	5210	Conventional	2005	(Mungkung et al. 2006)
Shrimp (Tiger Prawn)	Thailand	Attributional	901	Organic	2006	(Mungkung et al. 2006)
Shrimp (Tiger Prawn)	Philippines	Attributional	5108	Extensive pond polyculture	2008	(Baruthio, A., Aubin, J. Mungkung, R., Lazard, J., Van der Werf 2015)
Nile Tilapia	Indonesia	Attributional	2100	Flow-through Pond	2010	(Pelletier & Tyedmers 2010)
Nile Tilapia	Indonesia	Attributional	1520	Intensive Lake Net-Pen	2010	(Pelletier & Tyedmers 2010)
Nile Tilapia	Indonesia	Attributional	2255	Intensive Lake Net-Pen	2010	(Pelletier & Tyedmers 2010)
Rainbow trout	France	Attributional	2750	Flow-through raceway	2009	(Aubin et al. 2009)
Rainbow trout	France	Attributional	2040	Recirculating tank	2009	(Roque et al. 2009)
Rainbow trout	France	Attributional	2020	Flow-through tank	2009	(Roque et al. 2009)
Rainbow trout	France	Attributional	2220	Flow-through raceway	2011	(Boissy et al. 2011)
Rainbow trout	France	Attributional	2220	Flow-through raceway	2011	(Boissy et al. 2011)
Rainbow trout	France	Attributional	1805	Flow-through raceway	2003	(Aubin et al. 2009)
Rainbow trout	France	Attributional	2125	Flow-through raceway	2003	(Papatryphon et al. 2004)
Rainbow trout	France	Attributional	2595	Flow-through raceway	2003	(Papatryphon et al. 2004)
Turbot	France	Attributional	10640	Recirculating tank	2006	(Aubin et al. 2006)
Turbot	France	Attributional	6020	Recirculating tank	2006	(Aubin et al. 2006)
Turbot	France	Attributional	6020	Recirculating tank	2006	(Aubin et al. 2006)
Seaweed	UK	Attributional	19.2	Marine net-pen	2012	(Fry et al. 2012)
Mussels	UK	Attributional	252	Marine net-pen	2012	(Fry et al. 2012)
Mussels (Mediterranean)	Spain	Attributional	4.35	Extensive raft culture	2010	(Iribarren, Moreira, et al. 2010)
Mussels (Mediterranean)	Spain	Attributional	13.9	Extensive raft culture	2010	(Iribarren, Moreira, et al. 2010)
Mussels (Mediterranean)	Spain	Attributional	9.84	Extensive raft culture	2010	(Iribarren, Moreira, et al. 2010)

Mussels (Mediterranean)	Spain	Attributional	9.51	Extensive raft culture	2010	(Iribarren, Hospido, et al. 2010)
Oysters	UK	Attributional	1281	Marine net-pen	2012	(Fry et al. 2012)

Supplementary Table 1: Included LCA Studies. Listed life-cycle analysis (LCA) studies included in the current research.

Species (ISSCAAP group)	Rationale for GWP Selection	Species average GWP ($kgCO_2e/ton$)
Carps, barbels and other cyprinids	Assumed same as tilapia (same FCR)	1958
Salmons, trouts, smelts	Salmon; Trout; Arctic char	2357
Miscellaneous coastal fishes	Seabass	10712
Miscellaneous freshwater fishes	Catfish	8930
Shrimps, prawns	Shrimp	4193
Mussels	Mussels	58
Flounders, halibuts, soles	Turbot	7560
River eels	Assumed same as Flounders, Halibuts, Soles	7560
Clams, cockles, arkshells	Assumed same as Oysters	1281
Oysters	Oysters	1281
Tilapias and other cichlids	Tilapia	1958
Frogs and other amphibians	Assumed same as Flounders, Halibuts, Soles	7560
Sturgeons, paddlefishes	Assumed similar to Turbot	7560
Freshwater crustaceans	Assumed same as Shrimp	4193
Abalones, winkles, conchs	Assumed same as Oysters	1281
Miscellaneous aquatic invertebrates	Assumed same as Shrimp	1281
Miscellaneous diadromous fishes	Assumed same as Miscellaneous coastal fishes (Seabass)	10712
Miscellaneous marine crustaceans	Assumed same as Shrimp	4193
Crabs, sea-spiders	Assumed same as Shrimp	4193
Marine fishes not identified	Assumed same as Cod	3100
Scallops, pectens	Assumed same as Oysters	1281
Tunas, bonitos, billfishes	Assumed same as Flounders, Halibuts, Soles	7560
Miscellaneous pelagic fishes	Mackerel	540
Red seaweeds	Seaweed	19.2
Lobsters, spiny-rock lobsters	Assumed same as Shrimp	4193
Miscellaneous marine molluscs	Assumed same as Oysters	1281

Turtles	Assumed highest EF from review	10712
Green seaweeds	Seaweed	19.2
Miscellaneous aquatic plants	Assumed same as Seaweed	19.2
Cods, hakes, haddocks	Cod; Haddock	3100
Brown seaweeds	Seaweed	19.2
Freshwater molluscs	Assumed same as Oysters	1281
Pearls, mother-of-pearl, shells	Assumed same as Oysters	1281
Sea-urchins and other echinoderms	Assumed same as shrimp	4193
Miscellaneous demersal fishes	Assumed same as Flounders, halibuts, soles	7560
Shads	Assumed same as Salmon	2357
Squids, cuttlefishes, octopuses	Assumed same as shrimp	4193
Sea-squirts and other tunicates	Assumed very low and similar to mussels (filter-feeding invasive species with quick reproduction)	58

Supplementary Table 2: Applied Global Warming Potential (GWP) Emissions Factors (EFs) for each ISSCAAP category in current study.

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