The impact of global dietary guidelines on climate change

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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.

Keywords

sustainable nutrition; dietary guidelines; food; climate; protein; livestock

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).

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.

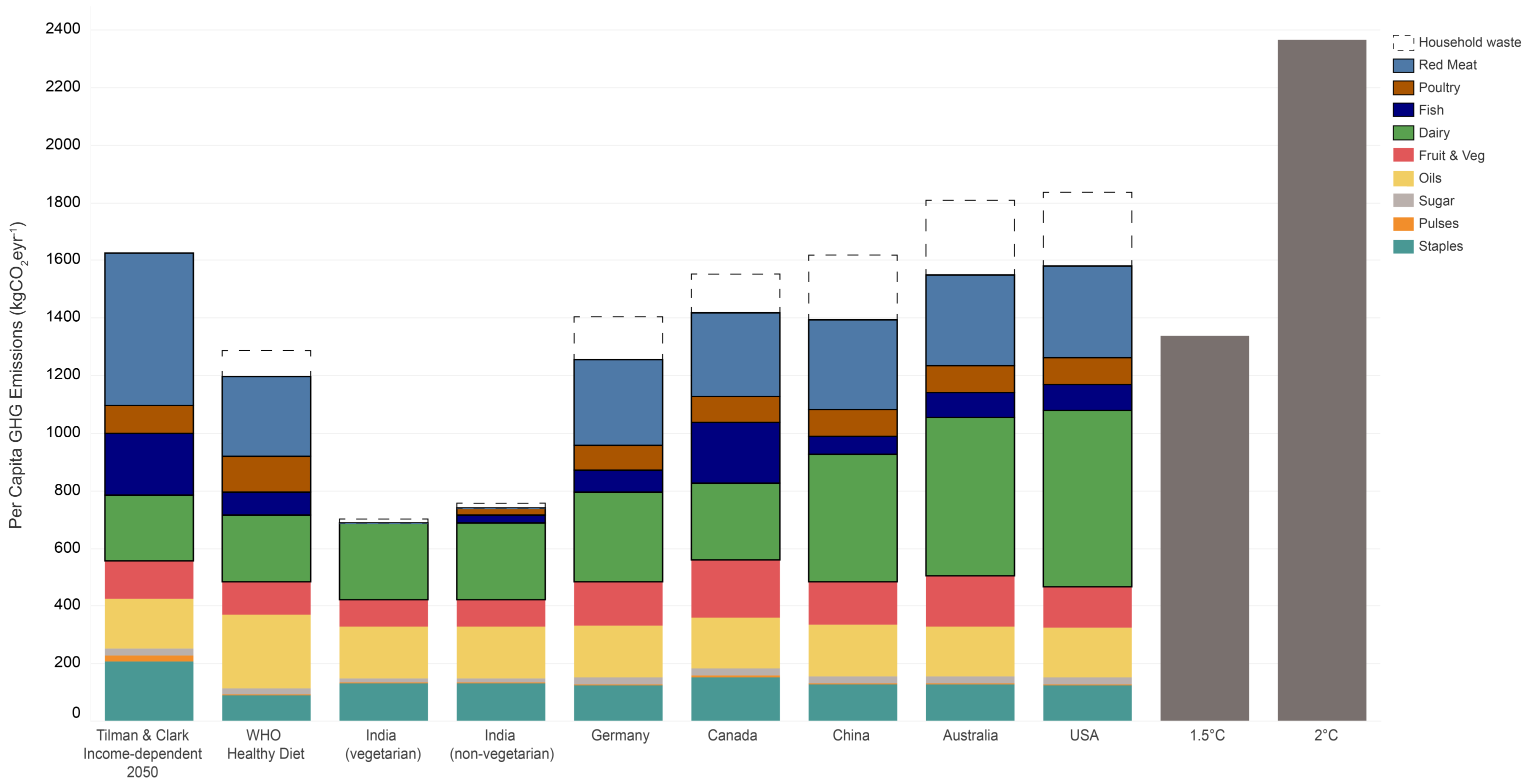


Figure 1: Per capita greenhouse gas emissions across income-dependent, WHO and national dietary guidelines. Annual breakdown of per capita food production (cradle-to-farmgate) emissions across the average income-dependent diet in 2050, WHO healthy diet, and national dietary guidelines by commodity group. 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.

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.

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.

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 421kgCO_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.

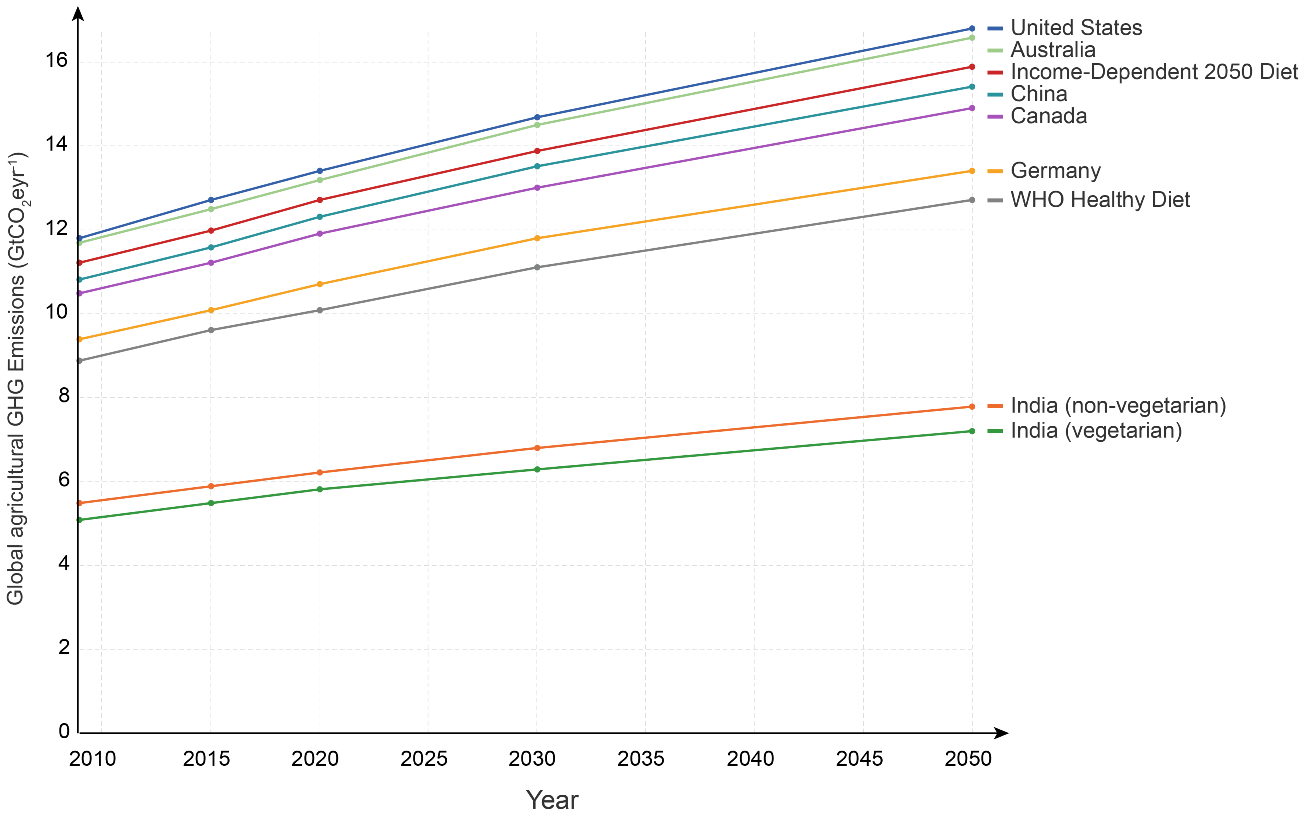
Of note in this analysis is the relatively low GHG emissions footprint of recommended diets in India – stemming from the unique nature of India's guidelines. Most nations detail meat and fish products as a core pillar of their dietary guides, with a smaller subset of countries providing an optional substitution 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.

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.

	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.

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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