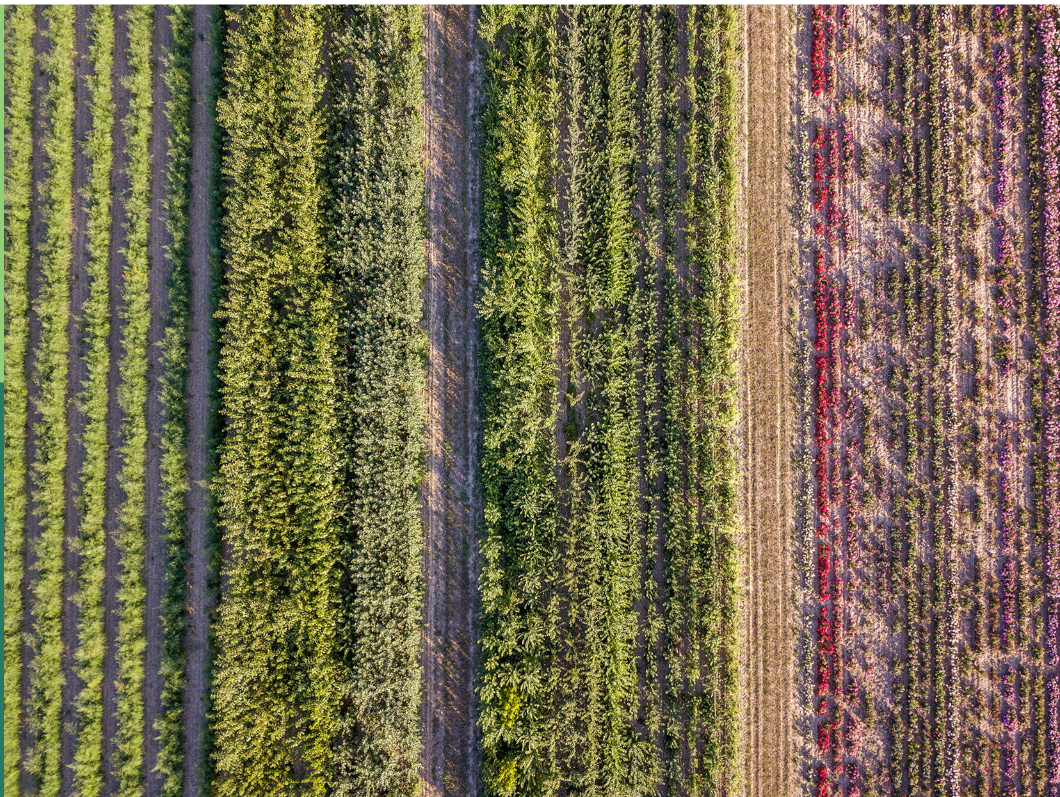
frontiers | Research Topics

Food systems evaluation methods and sustainability assessment

Edited by
Bradley George Ridoutt and Aida Turrini

Published in
Frontiers in Sustainable Food Systems



ISSN 1664-8714
ISBN 978-2-8325-4594-2
DOI 10.3389/978-2-8325-4594-2

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

Food systems evaluation methods and sustainability assessment

Topic editors
Bradley George Ridoutt — Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
Aida Turrini — Independent researcher, Scansano, Italy

Citation
Ridoutt, B. G., Turrini, A., eds. (2024). *Food systems evaluation methods and sustainability assessment*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-4594-2

Table of contents

frontiers | Frontiers in Sustainable Food Systems

TYPE Editorial
PUBLISHED 01 March 2024
DOI 10.3389/fsufs.2024.1372395

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
Tanushri Kaul,
International Centre for Genetic Engineering and Biotechnology, India

*CORRESPONDENCE
Aida Turrini
aida.turrini@gmail.com

RECEIVED 18 January 2024
ACCEPTED 12 February 2024
PUBLISHED 01 March 2024

CITATION
Turrini A and Ridoutt BG (2024) Editorial: Food systems evaluation methods and sustainability assessment.
Front. Sustain. Food Syst. 8:1372395.
doi: 10.3389/fsufs.2024.1372395

Editorial: Food systems evaluation methods and sustainability assessment

Aida Turrini[1]* and Bradley George Ridoutt[2,3]

[1]Independent Researcher, Scansano, Italy, [2]Commonwealth Scientific and Industrial Research Organisation (CSIRO) Agriculture and Food, Clayton, VIC, Australia, [3]University of the Free State, Department of Agricultural Economics, Bloemfontein, South Africa

KEYWORDS

sustainable food systems, evaluation methods, sustainability assessment, food system transition, sustainability metrics

Editorial on the Research Topic
Food systems evaluation methods and sustainability assessment

The Food System Countdown to 2030 was initiated to think about monitoring the food system transition toward "a future where all people have access to healthy diets, produced in sustainable, resilient ways, that restore nature and deliver just and equitable livelihood" (Fanzo et al., 2021). Recently, a food system indicator framework to track the transition was developed (Schneider et al., 2023).

The monitoring system is based on five pillars: (i) diets, nutrition, and health; (ii) environment, natural resources, and production; (iii) livelihoods, poverty, and equity; (iv) governance; and (v) resilience. In this context, the community of stakeholders and experts has identified 50 indicators that are valid *per se* and aligned with other indicator systems, including the Sustainable Development Goals, which are scheduled to be achieved before 2030 (Schneider et al., 2023).

Indicators are expected to reflect the complexity of the food system and the connectedness with several sectors concerning non-food components influencing the environment, social outcomes, and food consumption. The monitoring framework relies on data already collected and scheduled to be updated within the next 8 years (Schneider et al., 2023). During the observational period, the indicators can be integrated with other variables if considered relevant to the evaluation (Schneider et al., 2023). Therefore, in-depth insights can provide useful information to refine the monitoring framework.

The present topic collection comprises the originally considered topics (Table 1) as well as the themes of information and education as factors facilitating the food system transition. Specifically, it includes the information and education topic and the development of indicators to monitor specific aspects that have not yet been covered.

The literature review showed a limited availability of assessment methods for food system sustainability, which have only recently been developed (Fanzo et al., 2021; Sachs et al., 2023; Schneider et al., 2023). The article "*A scoping review of indicators for sustainable healthy diet*" focused on available methods to evaluate the sustainability of the food chain and its related impact on human health (Harrison et al.). The interest for alternative protein sources is increasingly growing, given the various recommendations for reducing meat intake for health and sustainability reasons. The article "*Alternative protein innovations and challenges for industry and consumer: an initial overview*" offers a preliminary overview for researchers and stakeholders in this field (Hefferon et al.).

TABLE 1 Topics related to food system evaluation considered in the Research Topic launch.

Integrated assessment of the entire food production and consumption from a life cycle perspective
Sustainability assessment case studies of specific industry segments
Consumer habits and perception survey
Integrated assessment of human health and environmental impacts of food production
Evaluation of the impact of traditional and innovative agricultural, farming, and fishing techniques
Food system components contributing to healthy and sustainable diets

The majority of published articles on this Research Topic are constituted by original research to try to identify overarching methods and indicators on specific aspects to disentangle innovative points at issue.

The approaches concerning the whole food system *per se* and in relation to climate change were discussed in two articles. A method based on a typical economic approach exploiting data from the global multi-regional input–output databases was used in the article "*Using input-output analysis to measure healthy, sustainable food systems*," providing indications for assessing the whole food system sustainability (Boylan et al.). The problem of estimating variables measuring environmental warming was discussed in "*Methane emissions from california dairies estimated using novel climate metric global warming potential star show improved agreement with modeled warming dynamics*" (Pressman et al.).

Specific components and approaches related to production innovation are analyzed in two articles: one dealing with primary production, such as agroecology in primary production ["Insights into agroecological farming practice implementation by conservation-minded farmers in North America" (Silva et al.] and another dealing with cropland ["*Estimating cropland requirements for global food system scenario modeling*" (Smith et al.]. Furthermore, the food consumption issue is the object of the article "*Assessing the diet quality, environmental impact, and monetary costs of the dietary transition in China (1997–2011): impact of urbanization*" (Chang et al.).

Finally, information and education to promote a healthy and sustainable diet are discussed in three articles: "*Simple eco-labels to nudge customers toward the most environmentally friendly warm dishes: an empirical study in a cafeteria setting*" (Slapø and Karevold), "*An approach for integrating and analyzing sustainability in food-based dietary guidelines*" (Mazac et al.), and "*Advancing an integrative framework to evaluate sustainability in national dietary guidelines*" (Ahmes et al.).

It is clear that production and consumption, i.e., the opposite extreme points of the food chain, are the most considered components in the food system transition. Moreover, information and education seem linked to healthy and sustainable food consumption but not to the production, distribution, or food service sectors.

Indicators included in the sustainability monitoring and assessment framework do not include the structure of the transformation or the distribution system at the national and/or international level, including trade agreements. Additionally, they do not include economics in general, except for the affordability of a healthy and sustainable diet (Sachs et al., 2023).

Industry and trade are crucial in supporting sustainability (OECD, 2022; Zimmermann and Rapsomanikis, 2023) because "trade is an integral part of our food systems. It connects people at all stages of agricultural and food value chains, linking farmers with consumers across the world. It also links nations to each other and thus scales up from the domestic to the global perspective. By moving food from surplus to deficit regions, trade promotes food security" (Zimmermann and Rapsomanikis, 2023). While creating economic opportunities for producers, including farmers and small and medium enterprises (SMEs) (OECD, 2022), "the diversity of foods available, and can affect preferences and diets. Trade impacts food prices and the allocation of resources, and thus is inherent to economic growth and interacts with the environment. At the same time, trade can create both winners and losers, resulting in inequality, and can generate negative social and environmental outcomes." (Zimmermann and Rapsomanikis, 2023). Trade enables food security while creating economic opportunities for producers, including farmers and small and medium enterprises (SMEs) (OECD, 2022). In this context, statistical data on economics can provide significant information. In this regard, the SUSFAN European research project approach (2015-2017) can be very helpful (SUSFANS Metrics, 2015).

In conclusion, integrating indicators from different suitable monitoring systems can provide comprehensive information. The Schneider et al. (2023) approach is characterized by openness to this option, which can be exploited as well.

Author contributions

AT: Writing—original draft, Writing—review & editing. BR: Writing—review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

Editors thank all the authors who submitted the manuscripts, adding important information to the Research Topic.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

References

Fanzo, J., Haddad, L., Schneider, K. R., Béné, C., Covic, N. M., Guarin, A., et al. (2021). Rigorous monitoring is necessary to guide food system transformation in the countdown to the 2030 global goals. *Food Policy* 104, 102163. doi: 10.1016/j.foodpol.2021.102163

OECD (2022). *Trade and Food System Transformation. Meeting of Agriculture Ministers*. Available online at: https://www.oecd.org/agriculture/ministerial/documents/Trade%20and%20Food%20Systems%20Transformation.pdf (accessed February 19, 2024).

Sachs, J. D., Lafortune, G., Fuller, G., and Drumm, E. (2023). *Implementing the SDG Stimulus. Sustainable Development Report 2023.* Dublin: Dublin University Press.

Schneider, K. R., Fanzo, J., Haddad, L., Herrero, M., Moncayo, J. R., Herforth, A., et al. (2023). The state of food systems worldwide in the countdown to 2030. *Nature Food.* 4, 1090–1110. doi: 10.1038/s43016-023-00885-9

SUSFANS Metrics (2015). *Models and Foresight for European Sustainable Food and Nutrition Security*. Available online at: www.susfans.eu (accessed February 19, 2024).

Zimmermann, A., and Rapsomanikis, G. (2023). Trade and sustainable food systems. *Sci. Innov. Food Syst. Transf.* 685, 1–14. doi: 10.1007/978-3-031-15703-5_36

frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 28 May 2019
doi: 10.3389/fsufs.2019.00040

Simple Eco-Labels to Nudge Customers Toward the Most Environmentally Friendly Warm Dishes: An Empirical Study in a Cafeteria Setting

Helena Berz Slapø[1,2]* and *Knut Ivar Karevold*[2]

[1] Oslo Metropolitan University, Oslo, Norway, [2] GreeNudge, Oslo, Norway

Background: Food production and consumption contributes to one third of households' environmental impact. The environmental impact of different food categories varies and in general environmental footprint of meat is high than fish and vegetable options. Environmental food labels have been suggested as a means to sway consumption patterns. The purpose of this study is to test if different simple eco-labels in combination with posters can influence consumers to select environmentally friendly food options.

Method: Three different labeling systems were tested on warm dishes in a University cafeteria in Oslo, Norway. The first system was traffic-light labels with three symbols (red, yellow and green), the second system was a single-green label that only labeled the environmentally friendliest dishes, and the third system was a single-red label that only labeled the least environmentally friendly option. Posters were placed in the cafeteria, explaining the labeling systems and the climate impact of different food categories. Outcome measures was sales share of meat, fish and vegetarian dishes. The intervention period was separated in two; the first 20 days (period 1) and 22 last days (period 2) to evaluate if the effects of the labels was different when first introduced and after some months.

Results: The traffic-light labels significantly reduced sales of meat dishes with 9% in the period 1 ($p < 0.1$) but not in period 2. Sales share of fish or vegetarian dishes were not impacted. Single-green and single-red labeling had no effect on sales share of meat, fish or vegetarian dishes. Posters were present during all interventions.

Conclusion: Findings suggests that traffic-light labels in combination with posters can improve the eco-friendliness of customers food choices in a cafeteria setting, at least short-term. Future studies should investigate the long-term effects of simple eco-labels. Additionally, one should study the combined effect of symbols with other changes in the choice architecture.

Keywords: food choices, behavioral economics interventions, nudging, eco-labels, simple-labels, environmental impact

OPEN ACCESS

Edited by:
Mark Andrew Lawrence, Deakin University, Australia

Reviewed by:
Catherine Georgina Russell, Deakin University, Australia
Aida Turrini, Council for Agricultural and Economics Research, Italy

****Correspondence:***
Helena Berz Slapø
helena@greenudge.no

Specialty section:
This article was submitted to Nutrition and Sustainable Diets, a section of the journal Frontiers in Sustainable Food Systems

Received: *14 September 2018*
Accepted: *02 May 2019*
Published: *28 May 2019*

Citation:
Slapø HB and Karevold KI (2019) Simple Eco-Labels to Nudge Customers Toward the Most Environmentally Friendly Warm Dishes: An Empirical Study in a Cafeteria Setting. Front. Sustain. Food Syst. 3:40. doi: 10.3389/fsufs.2019.00040

INTRODUCTION

Food production and consumption is responsible for one third of European households' total environmental impact and is an important sector from an environmental perspective (Guinée et al., 2006b; European Environment Agency, 2015). The livestock sector is the key contributor to greenhouse gas (GHG) emissions and alone accounts for 15% of total global emissions (Guinée et al., 2006a; Steinfeld et al., 2006; Nordic Council of Minsters, 2012; Gerber et al., 2013; National Institutes of Health, 2015; Nelson et al., 2016; Springmann et al., 2018). A growing body of research suggests that a global shift toward a more plant-based diet is necessary in order to overcome the worst climate change scenario (Goodland, 1997; Goodland and Anhang, 2009; Krystallis et al., 2009; Stehfest et al., 2009; Audsley et al., 2010; Deckers, 2010a,b; Freibauer et al., 2011; Gerber et al., 2013; Green et al., 2015; Fischer and Garnett, 2016). This can either be achieved by substituting meat-based diets with plant-based diets (Berners-Lee et al., 2012; Sabate and Soret, 2014; Scarborough et al., 2014) or by substituting high GHG intensive meat products (e.g., beef and lamb) with lower GHG intensive products (e.g., chicken and fish) (McMichael et al., 2007; Committee, 2008; Green et al., 2015).

Traditionally policymakers have tried to change peoples' food habits trough restricting the access or limiting marketing of certain foods, providing people with information and education or economic incentives to change food habits (Gorski and Roberto, 2015). Such interventions build on economic theory and models of rational decision-making, assuming that human choices are reason based, rational and logical (Hollands et al., 2013). Some recent reviews have argued that such interventions have unclear effects on people's actual food choices (Grunert and Wills, 2007; Capacci et al., 2012; Wills et al., 2012). One explanation is the gap between knowledge and attitudes and actual behaviors, and that people make a high number of food choices every day making it difficult to adhere to all positive intentions (Camerer, 2003). Since food choices are often not planned in detail these purchases are largely characterized by habits and intuition (Meiselman and Bell, 2003).

Researchers, policy-makers, private companies and practitioners alike are therefore looking toward the relatively new field of behavioral economics for other interventions that may be better suited to change choices (Hallsworth et al., 2018). According to behavioral economics, many daily decisions are fast, intuitive and occur outside cognitive awareness (Sunstein and Thaler, 2008; King et al., 2013). By changing the context or decision architecture, people may be nudged toward better choices (Marteau et al., 2011). Changing the food environment and presentation of food options may therefore influence customers' food choices without removing options or changing economic incentives (Sunstein and Thaler, 2008).

Nudging involves changing the sequence of options presented and the available information about the options at the moment of choice (Sunstein and Thaler, 2008). Introducing environmental labels (eco-labels) can be considered adding information about the food choices. Some scholars have questioned if eco-labels qualify as 'nudges' and should be considered as a traditional informative intervention (Kosters and Van der Heijden, 2015), while others argue that eco-labels provide additional information at the point of choice and therefore qualify as nudges (Ölander and Thøgersen, 2014). Simple labels that do not require high levels of literacy and numeracy (Rothman et al., 2006), and that reduce information overload are defined as simple labeling nudges (Iyengar and Lepper, 2000; Mitchell et al., 2005; Karevold et al., 2017) and are the labels this study investigates.

Eco-Labeling to Change Food Choices in a Cafeteria Setting

To our knowledge no studies have investigated the effect of simple labels as a strategy to get customers to change their food choices toward more eco-friendly options in a cafeteria. However, we have identified six reviews that have studied how labels and signs can influence consumers in cafeterias to eat healthier (Swartz et al., 2011; Hersey et al., 2013; Kiszko et al., 2014; Sinclair et al., 2014; Long et al., 2015; Fernandes et al., 2016). All reviews concluded that there is minimum evidence that supports the use of calorie labeling in cafeterias (Swartz et al., 2011; Kiszko et al., 2014; Sinclair et al., 2014; Long et al., 2015; Fernandes et al., 2016). The authors explained that the reason may be that detailed calorie labels only work on certain groups as women and health-conscious consumers (Swartz et al., 2011; Kiszko et al., 2014; Sinclair et al., 2014; Long et al., 2015). Two of the reviews argued that simple labels as traffic-light labels or labels that identify the best option attract more attention than detailed labels (Hersey et al., 2013; Fernandes et al., 2016). Therefore, simple labels may be more effective than numeric and detailed labels (Hersey et al., 2013; Fernandes et al., 2016).

Several studies on traffic-light labels found that they reduced the intake of unhealthy food products (Variyam et al., 1995; Borgmeier and Westenhoefer, 2009; Thorndike et al., 2012; Madhvapaty and DasGupta, 2015). It has been argued that traffic-light labels work well because consumers intuitively grasp the implicit messages of the relative colors and are able to compare options within the same category (Bargh, 1992). Another stream of research has studied how introducing a third option influences preferences, also called the compromise effect (Carroll and Vallen, 2014). The compromise implies that the middle option becomes more attractive or popular when a smaller or larger option is introduced, compared to when only the two extremes are available. In a calorie labeling study, customers avoided the largest and smallest caloric items and chose the items in-between (Carroll and Vallen, 2014). In another study, the middle size became more likely to be purchased when a larger and a smaller drink size option was added to the range of choices (Sharpe et al., 2008). Traffic-light labels may therefore lead to an increase in purchase of the middle option.

Simple signs may serve as reference points, indicating that an option has positive or negative characteristics. Previous research has investigated how reference points can lead to positive and negative contrast effects (Kahneman and Tversky, 1979, 2000, 2013; Kahneman, 1992). A reference point will typically influence people to experience options that are better as positive, while those under the reference point as negative (Kahneman and Tversky, 1979). Single positive signs such as a green label can communicate that an option is positive, while a red sign can imply a negative warning or signal not to choose. Introducing a single green label can make the other options seem less attractive and influence a reduced selection of these while increasing the consumption of the green option. On the other hand, a single-red label can make the other options seem more attractive and perhaps reduce the attraction of the red option.

A major gap in the literature is if simple food labels work over time in settings there customers are exposed to labels multiple times. None of the six reviews looked at the long-term effects of food labels. Thorndike et al. (2014) argued that customers develop "fatigue" for labels when exposed to them multiple times and that labels therefore stop working after some time (Thorndike et al., 2014). It is therefore important to determine the impact of eco-labels on real food purchase over time.

Cafeterias can be a venue for swaying food choices, as more and more meals are consumed in this context all over the western world (The Nielsen Company, 2016). If simple eco-labels can promote environmentally friendly choices, this can be a low-cost intervention to influence a high number of food choices for a high number of people in the population.

This paper makes several contributions. Our paper is the first to compare the effects of three different simple eco-label systems on environmentally friendlier food alternatives in a cafeteria setting. Previous studies have tested eco-labels in grocery stores (Vanclay et al., 2011; Elofsson et al., 2014; Vlaeminck et al., 2014). Further, this study investigates the effects of eco-labels on actual food choices. Previous studies have assessed attitudes and intentions that do not necessarily translate into actual food choices (Chatzidakis et al., 2007; de Boer et al., 2009; Krystallis et al., 2009; Bray et al., 2011; de Barcellos et al., 2011; Brouhle and Khanna, 2012).

Hypothesis

Based on the discussion above, we expect simple eco-labeling systems to impact consumers' food choices. A green sign is expected to function as a positive contrast and a red sign is expected to function as a negative contrast. This study will investigate the effects of three different simple labels; a traffic-light, a single-green label and a single-red label.

Thus, the present study explores three hypotheses:

Hypotheses (1): The three-colored traffic-light labeling will stimulate customers to choose more of the green-labeled dishes and yellow-labeled dishes, and less of the red-labeled dishes.

Hypotheses (2): The single-green labeling will stimulate customers to choose more of the green-labeled dishes, and less of the two other dishes.

Hypotheses (3): The single-red labeling will stimulate customers to choose less of the red-labeled dishes, and more of the two other dishes.

METHODS

Intervention

As shown in **Figure 1**, the traffic-light system labeled all three warm dishes, while the single-green and single-red marked one single dish on the menu. For the single-green labeling format only the vegetarian dish was labeled with the "Low CO_2" sign. In contrast, the single-red labeling format exclusively marked the meat dish with a "High CO_2" label.

As previously discussed, the environmental footprint of meat, fish and vegetarian diets are significantly different from each other. Based on a general categorization of these differences, all meat dishes were labeled as "High CO_2" dishes, all fish dishes as "Medium CO_2" and all vegetarian as "Low CO_2" dishes. The labels used a simple color-coded scheme in combination with words inside the labels to visualize the environmental impact of the dish, which has been found to improve the efficacy of eco-labels (Tang et al., 2004).

The labels were placed on the menu board next to the dish description where consumers ordered their food. Menu labeling made sure that consumers were exposed to the active labeling formats during the time of decision making. Photos illustrating the placement of the labels on the menu board are provided in **Appendix A**.

In addition to labels, posters were placed in the cafeteria, explaining the labeling system and the climate impact of the different food categories. The posters are shown in **Appendix B**. Based on Golan et al.'s (2001) and Weiss and Tschirhart (1994) recommendations, information on the posters was held clear, concise and informative to avoid the possibility of information overload (Golan et al., 2001) and correspond with assumed prior knowledge of the target audience (Weiss and Tschirhart, 1994). We expected customers to have knowledge about carbon dioxide impact on climate change. However, we did not assume consumers as much knowledge about the environmental consequences of food production. The posters therefore did not explain carbon dioxide but focused on meat products' environmental impact. The posters were placed both at the entrance of the cafeteria and on a shelf next to the warm dishes. Besides, table cards with the same design as the posters were placed on the tables in the cafeteria.

Research Setting

This study was conducted in the largest cafeteria at the campus of the University of Oslo. The cafeteria sold three different warm dishes every day; one meat, one fish, and one vegetarian dish, in addition to other products. Warm dishes were selected for analysis, firstly because it was relatively easy to estimate the environmental impact of the different dish categories, and secondly because the price was the same for all dishes and constant during the study period. The cafeteria was open five days a week and served warm dishes from 11:00 a.m. to 6:00 p.m. Monday to Thursdays. Fridays were not included in the sample due to short opening hours (until 3:00 p.m.).

Control sales data were collected for 17 days prior to intervention. We used a pre-intervention control period and no parallel control period so that the measured purchase behavior

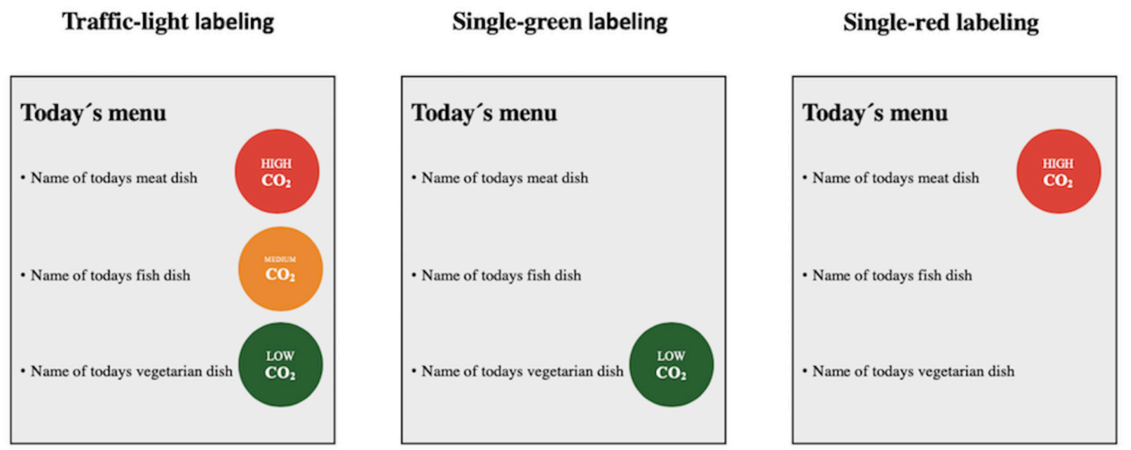


FIGURE 1 | The three different labeling systems used in the experiment.

during the control period was completely unaffected by the labeling intervention. We aimed to provide enough time to detect an effect on sales of the labeling intervention and similar duration for the intervention periods. The intervention period was 42 days and the Christmas holidays divided the intervention period. Since it is likely that many of the same guests visited the cafeteria several times, this gave us the opportunity to compare the effect of the labels when first introduced and after several months. Sales data were collected for the 22 days before the Christmas holidays (period 1) and 22 days after the holidays (period 2) separately. Two days in fall were taken out of the sample because the cafeteria sold out of warm dishes. Intervention period 1 was therefore reduced from 22 days to 20 days.

Since we in this study compared the effects of the different labeling systems, we needed to make sure that the impact of "popular dishes" was not mistaken for the effect of the labeling intervention. We therefore rotated the three labeling systems during each day of the intervention. Each day was divided into three time periods: late morning (11:00 a.m.−01:00 p.m.), early afternoon (01:00–03:00 p.m.) and late afternoon from (03:00–06:00 p.m.). The different labeling-systems randomly rotated between the different time periods each day. Thus, an even distribution amongst the three labeling designs was ensured during each measurement day. When the different labeling systems were at place is shown in **Appendix C**.

Output Data

Information about number of warm dishes sold was collected from the cash registry. The cafeteria's cash registers were programmed to capture the information needed to identity the different warm dishes, the time and day of sale. The cafeteria staff was informed about the purpose of the experiment and they were asked to not influence the customers' dish choices. Since the study aimed to identify the labeling treatments' effect on relative changes in dish purchases, the sales data were converted from absolute numbers into share of total sales each day. By using shares of total sale, we accounted for weekly fluctuations in number of sales of the warm dishes as a whole.

Data Analysis

Ordinary Least Squares regression (OLS) was used to analyze the impact of the labeling systems on sales share of different dishes. The regression controlled for other variables not captured by the labeling systems in order to best isolate the true relationship between the sales share of dishes under different labeling systems. We controlled for the effect of weekday and time of the day in the regression. Independent variables were categorical and were converted to binary dummy variables before serving as inputs for the estimated regression model. The results from the statistical tests were considered significant for $p = 0.1$. Regression results are shown in **Appendix D**.

We did not register any information about the individual guests and their personal choices. The guests in the cafeteria were staff and students working in this section of the campus, and it is probable that the same guests visited the restaurant on several occasions during the intervention periods. The observations of sales data are therefore not independent observations. Our study design allows us to investigate the effects of eco-labels on the food choices of the same guest over time.

RESULTS

The total number of observations was 228; control period 51 observations (3 per day × 17 days), 60 observations in intervention period 1 (3 per day × 20 days), and 66 in intervention period 2 (3 per day × 22 days).

Figure 2 shows the daily sales share of the three different warm dishes in the cafeteria before and after the introduction of the labeling systems.

Sales of meat dishes was higher than sales of vegetarian dishes during the whole period, indicating that meat dishes in general were more popular than vegetarian and fish dishes. In addition, sales of the different warm dishes highly fluctuated from day to

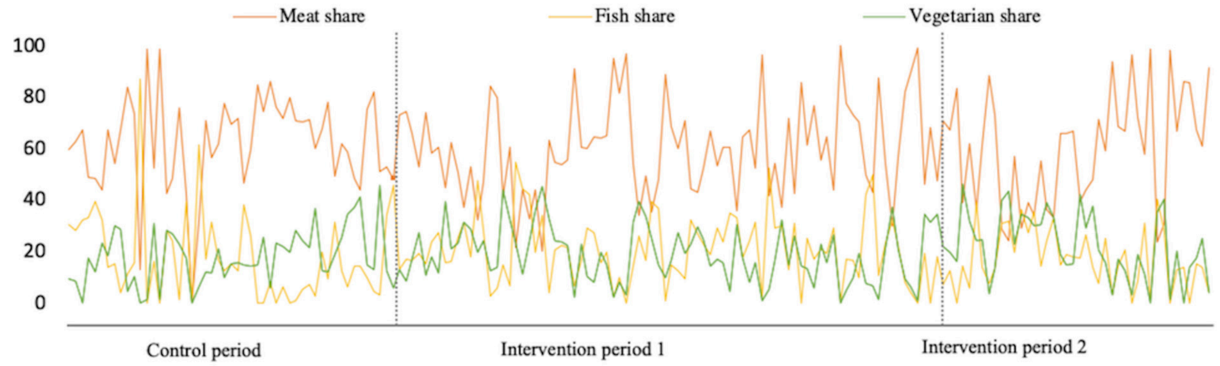


FIGURE 2 | Percentage share of different dishes of total sales during control period and intervention periods.

day, leading to a high variation in daily sales data. Sales share for each day during the experiment are shown in **Appendix E**.

Hypotheses Testing

Hypotheses (1) was that the three-colored traffic-light labeling will stimulate customers to choose more of the green-labeled dishes and yellow-labeled dishes, and less of the red-labeled dishes.

Figure 3 shows the share of different dishes under the control and the different intervention periods under traffic-light labeling.

Results from the regression analysis show that traffic-light labeling did not significantly impact sales share of green-labeled vegetarian or yellow-labeled fish dishes on any of the intervention periods ($p > 0.1$). For meat dishes the results show that traffic-light labeling reduced sales with 9% in period 1 and that traffic-light labeling can explain about 7% of the reduction (COEF traffic-light $= -0.069$, $p = 0.10$). Traffic-light labeling did not have a significant effect on sales of meat dishes during the second intervention period ($p = 0.38$).

Hypotheses (2) was that the single-green labeling will stimulate customers to choose more of the green-labeled dishes, and less of the two other dishes.

Figure 4 shows the share of different dishes under the control period and the different intervention periods under single-green labeling. Under this system only the vegetarian dish was marked with a green label.

The results from the regression analysis show that the single-green labels did not sway customers to choose more of the green-labeled vegetarian dishes ($p > 0.1$) nor less of the meat or fish dish ($p > 0.1$).

Hypotheses (3) was that the single-red labeling will stimulate customers to choose less of the red-labeled dishes, and more of the two other dishes.

Figure 5 shows the sales share of different dishes under the control period and the different intervention periods under single-red labeling. Here only the meat dish was marked with a red label.

According to the analysis the introducing the single red-label did not sway customers to choose less of the red-labeled meat dishes ($p > 0.1$) nor more of the vegetarian or fish dish ($p > 0.1$).

DISCUSSION

This experiment tested three different simple labels to promote eco-friendly food choices in a cafeteria setting. We expected that all three simple labels would improve the eco-friendliness of food choices.

However, we found that only the traffic-light labels significantly influenced customers to choose less meat dishes and only during period 1, but the traffic-light labels did not significantly increase sales of more environmentally friendly options. The effects of the traffic-lights suggest that the red traffic-light stopped some customers from going for the least eco-friendly option, but that the green lights did not make more customers go for the most eco-friendly option. However, the traffic-lights effects seemed to be time limited and faded away in the second intervention period since we only observed a significant change during the first intervention period.

The results suggest that the traffic-lights led to a switch from red choices to the yellow middle option. Sales of the green labeled vegetarian dish did not increase as much as sales of the middle yellow labeled fish dish. This can be interpreted as support for the compromise effect (Carroll and Vallen, 2014), meaning that the traffic-light labeling led to an increase of the middle option, and not to a switch to the more extreme green option. Another interpretation of the same result might be that meat hungry guests prefer fish proteins to pure vegetarian meals and that the meat and fish dish were considered more simulate to each other than a vegetarian dish.

The single green- and red-light systems did not sway food choices in a systematic direction. One explanation for the weak influence of the single eco-label might be that these contained even less information than the traffic-lights with comparable references. The single symbols might have been difficult to make sense of, as environmental labeling was a newly introduced marker on the dishes and customers did not have any prior knowledge about the labels used in this study.

We considered the cafeteria setting to be a relatively low involvement choice setting where customers less actively process available information about the food alternatives (Meiselman and Bell, 2003; Karevold et al., 2017). Therefore, it may be

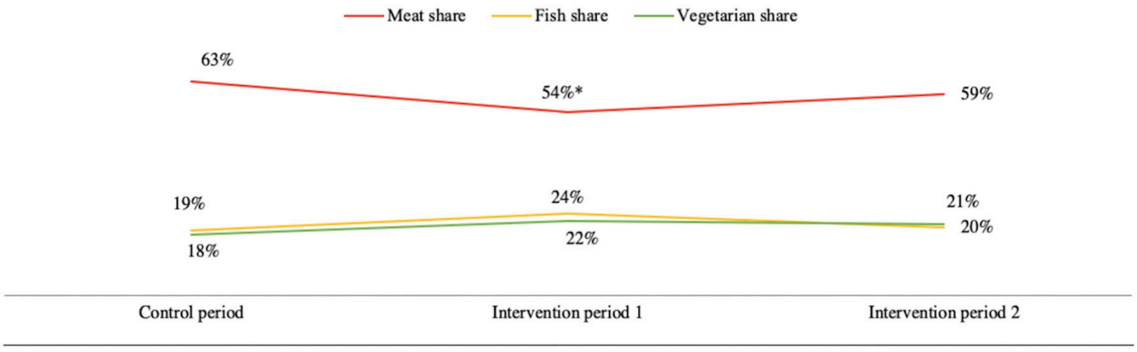


FIGURE 3 | Sales share of different dishes under traffic-light labels vs. no labeling. * indicates significance difference at the 90% significance level.

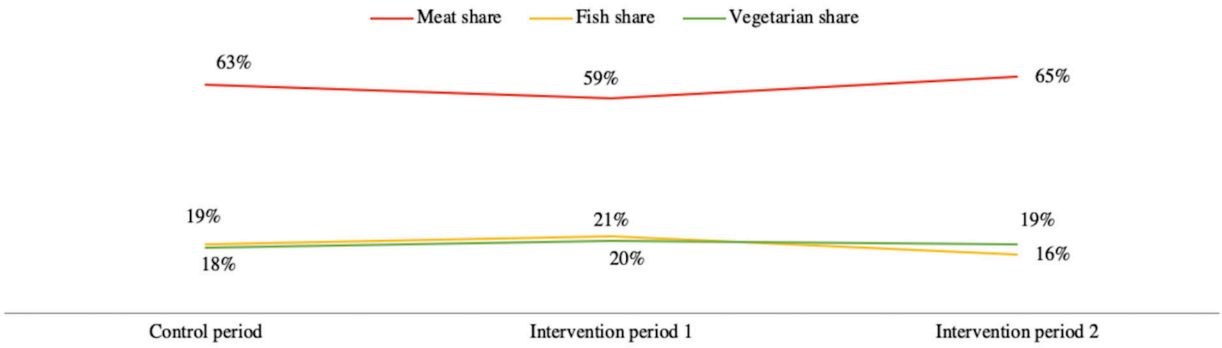


FIGURE 4 | Sales share of different dishes under single-green labels vs. no labeling.

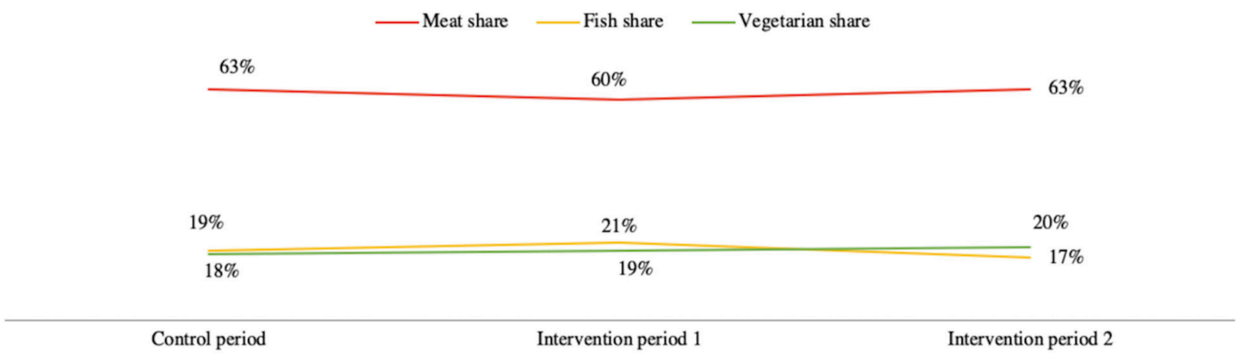


FIGURE 5 | Sales share of different dishes under single-red labels vs. no labeling.

that costumers did not notice the labels. Also, perhaps the guests had limited previous knowledge about the connection between food choices and environmental consequences. In addition, perhaps the environmental signage was inconsistent with the guests' perceived need in the choice situation; the guests might have been more focused on effective delivery of a tasty meal than preserving the environment through eating something different. It may be that costumers had low environmental awareness or motivation to make eco-friendly.

We expected that the same set of customers were exposed to the labels during intervention period 1 and 2. Customers seemed to react favorable to the traffic-light label when first introduced, but their eco-friendly behavior declined over time and almost returned to control period behavior after some months during period 2. These results could be seen as an evidence for customers developing "fatigue" for the labels and that the effect of the eco-labels in this study was only relatively short lived. These findings may reflect typical customer behaviors and reactions to signage (Thorndike et al., 2014).

STRENGTHS AND LIMITATIONS

A notable strength of the study is that we measured changes in actual purchase choices rather than relying on self-reported behavior. This is important as previous studies suggest that people in general exaggerate their environmentally friendly behavior when responding to questionnaires (Chatzidakis et al., 2007; de Boer et al., 2009; Bray et al., 2011). Using real sales data may have limited our ability to control for external factors or events that might have occurred during the cafeteria intervention compared to a laboratory experiment, but still showed what the guests actually preferred.

By using the cafeteria's overall design for the labels and for posters (colors, typography and logos) we camouflaged the experiment and limited the risk influence of social desirability and other third variables. Since the customers were not aware that they were part of an experiment, they were less liable to modify their behavior in a socially desirable direction (Benz and Meier, 2008; Monahan and Fisher, 2010). Influencing the customers to believe that the labels and posters originated from the cafeteria operator may have increased the labels and posters credibility (Weiss and Tschirhart, 1994). Since the cafeteria employees collected sales data electronically through the cash register, customers were not aware that their food purchase was being analyzed. This reduced the risk of researcher and participant bias. This supports that the observed effect was strongly related to the intervention as opposed to any other confounding bias.

A strength of the study is that we rotated the interventions in a random manner for each observation day. Another strength is that we split the intervention periods in two, naturally divided by the Christmas holidays. As the guests were from the same area of the campus, we expect that same set of guests was exposed to several different versions of the signage during the period, but that this did not skew the results in a systematic way as the interventions were rotated randomly.

A limitation of the study is the relatively low number of observations ($n = 228$). Due to day-to-day variations in sales shares, it was difficult to detect a clear trend caused by the interventions. In addition, the labeling system only included warm dishes. One may argue that the labeling system would have had a greater and more detectable effect on sales if all food products in the cafeteria had been labeled. This would have allowed customers to more directly compare the environmental information provided by the labels across products.

Another limitation was that we could not separate the effect of the labels to the effect of the posters, as posters were visible to customers during the entire intervention period. As we did not collect information about the individual customers, we do not know how the guests perceived the signs and labels during the process of choosing what to eat.

CONCLUSIONS

This study suggests that traffic-light labeling according to the environmental impact of different dishes in combination with posters might have an effect, but that the effects may fade over time. Labeling of the eco-friendliest or lest eco-friendly dish does not seem to sway food choices in an environmentally friendly direction. Further studies should test the use of traffic-light labels for a longer period of time to determine if the label can have long-term effects on food choices.

As meat consumption has a significant negative environmental foot print, and more traditional policy interventions do not fully seem to capture peoples' motivations when choosing what to eat, behavioral economics interventions can be relevant future area of research. Future studies could combine signage tools with other nudge interventions to assess the combined effect of symbols with other changes in the choice architecture. It might be beneficial to look into the research on choice architecture interventions for health food choices as a reference.

ETHICS STATEMENT

An ethics approval was not required as per the guidelines from Norwegian School of Economics, nor the Norwegian research ethics committees' guidelines. The participants in the study were anonymous cafeteria customers and diners at a University of Oslo cafeteria. No information about the guests was collected. We only collected information about the number of food choices in the restaurant. No oral informed consent was obtained from the participants, and no other another consent procedure were followed.

AUTHOR CONTRIBUTIONS

HS designed the study and collected the date as part of her master thesis at the Norwegian School of Economics under supervision of Mathias Ekström (https://openaccess.nhh.no/nhh-xmlui/bitstream/handle/11250/2404108/masterthesis.pdf?sequence=1). HS analyzed the data and was primary responsible for the final content. KIK contributed the writing of the paper. All authors have approved the final manuscript.

ACKNOWLEDGMENTS

This paper is based on the HS master thesis at the Norwegian School of Economics. We thank supervisor Mathias Ekström for his contribution to the design of the study. We also thank Per Chistensen, Inger-Merethe Seljeseth and the entire cafeteria staff at the Faculty of Social Sciences at the University of Oslo for their cooperation, and enthusiasm during the study.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2019.00040/full#supplementary-material

Data Sheet 1 | Appendix A, B, C, D, and E.

REFERENCES

Audsley, E., Brander, M., Chatterton, J. C., Murphy-Bokern, D., Webster, C., and Williams, A. G. (2010). *How Low Can We Go? An Assessment of Greenhouse Gas Emissions from the UK Food System and the Scope Reduction by 2050*. Report for the WWF and Food Climate Research Network.

Bargh, J. A. (1992). The ecology of automaticity: toward establishing the conditions needed to produce automatic processing effects. *Am. J. Psychol.* 105, 181–199. doi: 10.2307/1423027

Benz, M., and Meier, S. (2008). Do people behave in experiments as in the field?—evidence from donations. *Exp. Econ.* 11, 268–281. doi: 10.1007/s10683-007-9192-y

Berners-Lee, M., Hoolohan, C., Cammack, H., and Hewitt, C. (2012). The relative greenhouse gas impacts of realistic dietary choices. *Energy Pol.* 43, 184–190. doi: 10.1016/j.enpol.2011.12.054

Borgmeier, I., and Westenhoefer, J. (2009). Impact of different food label formats on healthiness evaluation and food choice of consumers: a randomized-controlled study. *BMC Public Health* 9:184. doi: 10.1186/1471-2458-9-184

Bray, J., Johns, N., and Kilburn, D. (2011). An exploratory study into the factors impeding ethical consumption. *J. Business Ethics* 98, 597–608. doi: 10.1007/s10551-010-0640-9

Brouhle, K., and Khanna, M. J. E. E. (2012). Determinants of participation versus consumption in the Nordic Swan eco-labeled market. *Ecol. Econ.* 73, 142–151. doi: 10.1016/j.ecolecon.2011.10.011

Camerer, C. F. (2003). *Behavioural Economics: Past, Present and Future*. Pittsburgh. Retrieved from: http://www.its.caltech.edu/$\sim$camerer/ribe239.pdf

Capacci, S., Mazzocchi, M., Shankar, B., Macias, J. B., Verbeke, W., Pérez-Cueto, F. J., et al. (2012). Policies to promote healthy eating in Europe: a structured review of policies and their effectiveness. *Nutr. Rev.* 70, 188–200. doi: 10.1111/j.1753-4887.2011.00442.x

Carroll, R., and Vallen, B. (2014). Compromise and attraction effects in food choice. *Int. J. Consumer Stud.* 38, 636–641. doi: 10.1111/ijcs.12135

Chatzidakis, A., Hibbert, S., and Smith, A. P. (2007). Why people don't take their concerns about fair trade to the supermarket: the role of neutralisation. *J. Business Ethics* 74, 89–100. doi: 10.1007/s10551-006-9222-2

Committee, C. C. (2008). *Building a Low-Carbon Economy-the UK's Contribution to Tackling Climate Change*. Norwich. Retrieved from: https://www.theccc.org.uk/wp-content/uploads/2008/12/Building-a-low-carbon-economy-Committtee-on-Climate-Change-2008.pdf

de Barcellos, M. D., Krystallis, A., de Melo Saab, M. S., Kügler, J. O., and Grunert, K. G. (2011). Investigating the gap between citizens' sustainability attitudes and food purchasing behaviour: empirical evidence from Brazilian pork consumers. *Int. J. Consumer Stud.* 35, 391–402. doi: 10.1111/j.1470-6431.2010.00978.x

de Boer, J., Boersema, J. J., and Aiking, H. (2009). Consumers' motivational associations favoring free-range meat or less meat. *Ecol. Econ.* 68, 850–860. doi: 10.1016/j.ecolecon.2008.07.001

Deckers, J. (2010a). Should the consumption of farmed animal products be restricted, and if so, by how much? *Food Pol.* 35, 497–503. doi: 10.1016/j.foodpol.2010.06.003

Deckers, J. (2010b). What policy should be adopted to curtail the negative global health impacts associated with the consumption of farmed animal products? *Res Publ.* 16, 57–72. doi: 10.1007/s11158-010-9117-z

Elofsson, K., Matsdotter, E., and Arntyr, J. (2014). *Got Green Milk?: A Field Experimental Trial of Consumer Demand for a Climate Label*. Institutionen för Ekonomi, Sveriges lantbruksuniversitet.

European Environment Agency. (2015). *Agriculture and Climate Change*. Copenhagen. Retrieved from: https://www.eea.europa.eu/signals/signals-2015/articles/agriculture-and-climate-change

Fernandes, A. C., Oliveira, R. C., Proença, R. P., Curioni, C. C., Rodrigues, V. M., and Fiates, G. M. (2016). Influence of menu labeling on food choices in real-life settings: a systematic review. *Nutr. Rev.* 74, 534–548. doi: 10.1093/nutrit/nuw013

Fischer, C. G., and Garnett, T. (2016). *Plates, Pyramids, and Planets: Developments in National Healthy and Sustainable Dietary Guidelines: A State of Play Assessment*. Food and Agriculture Organization of the United Nations.

Freibauer, A., Mathijs, E., Brunori, G., Damianova, Z., Faroult, E., i Gomis, J. G., et al. (2011). Sustainable Food Consumption and Production in a Resource-constrained World Summary Findings of the EU SCAR Third Foresight Exercise La production et la consommation alimentaires durables dans un monde aux ressources limitées Résumé des résultats du 3ème exercice de prospective du Comité permanent pour la recherche agricole de l'Union européenne Nachhaltiger Lebensmittelkonsum und nachhaltige Lebensmittelproduktion in einer Welt mit begrenzten Ressourcen Zusammenfassung der Ergebnisse aus dem dritten Vorausschauverfahren des Ständigen Agrarforschungsausschusses (SCAR) der EU. *EuroChoices* 10, 38–43. doi: 10.1111/j.1746-692X.2011.00201.x

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). *Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities*. Food and Agriculture Organization of the United Nations (FAO).

Golan, E., Kuchler, F., Mitchell, L., Greene, C., and Jessup, A. (2001). Economics of food labeling. *J. Consumer Pol.* 24, 117–184. doi: 10.1023/A:1012272504846

Goodland, R. (1997). Environmental sustainability in agriculture: diet matters. *Ecol. Econ.* 23, 189–200. doi: 10.1016/S0921-8009(97)00579-X

Goodland, R., and Anhang, J. (2009). *Livestock and Climate Change: What if the Key Actors in Climate Change are... Cows, Pigs, and Chickens? Livestock and Climate Change: What if the Key Actors in Climate Change are... Cows, Pigs, and Chickens?*

Gorski, M. T., and Roberto, C. A. (2015). Public health policies to encourage healthy eating habits: recent perspectives. *J. Healthc. Leadership* 7:81. doi: 10.2147/JHL.S69188

Green, R., Milner, J., Dangour, A. D., Haines, A., Chalabi, Z., Markandya, A., et al. (2015). The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. *Climat. Change* 129, 253–265. doi: 10.1007/s10584-015-1329-y

Grunert, K. G., and Wills, J. M. (2007). A review of European research on consumer response to nutrition information on food labels. *J. Public Health* 15, 385–399. doi: 10.1007/s10389-007-0101-9

Guinée, J., Heijungs, R., De Koning, A., Van, L., Geerken, T., Van Holderbeke, M., et al. (2006a). *Environmental Impact of Products (EIPRO) Analysis of the Life Cycle Environmental Impacts Related to the Final Consumption of the EU25*. Retrieved from: http://ec.europa.eu/environment/ipp/pdf/eipro_report.pdf

Guinée, J., Heijungs, R., De Koning, A., Van, L., Geerken, T., Van Holderbeke, M., et al. (2006b). *Environmental Impact of Products (EIPRO) Analysis of the Life Cycle Environmental Impacts Related to the Final Consumption of the EU25*.

Hallsworth, M., Egan, M., Rutter, J., and McCrae, J. (2018). *Behavioural Government: Using Behavioural Science to Improve How Governments Make Decisions. The Behavioural Insights Team*. London. Retrieved from: https://www.bi.team/wp-content/uploads/2018/08/BIT-Behavioural-Government-Report-2018.pdf

Hersey, J., Wohlgenant, K., Arsenault, J., Kosa, K., and Muth, M. (2013). Effects of front-of-package and shelf nutrition labeling systems on consumers. *Nutr. Rev.* 71, 1–14. doi: 10.1111/nure.12000

Hollands, G. J., Shemilt, I., Marteau, T. M., Jebb, S. A., Kelly, M. P., Nakamura, R., et al. (2013). Altering micro-environments to change population health behaviour: towards an evidence base for choice architecture interventions. *BMC Public Health* 13:1218. doi: 10.1186/1471-2458-13-1218

Iyengar, S. S., and Lepper, M. R. (2000). When choice is demotivating: can one desire too much of a good thing? *J. Personal. Soc. Psychol.* 79:995. doi: 10.1037//0022-3514.79.6.995

Kahneman, D. (1992). Reference points, anchors, norms, and mixed feelings. *Organ. Behav. Human Decision Processes* 51, 296–312. doi: 10.1016/0749-5978(92)90015-Y

Kahneman, D., and Tversky, A. (1979). Prospect theory: an analysis of decision under risk. *Econ. J. Econ. Soc.* 47, 263–291. doi: 10.2307/1914185

Kahneman, D., and Tversky, A. (2000). Choices, values, and frames. *Am. Psychol.* 39, 341–350. doi: 10.1037//0003-066X.39.4.341

Kahneman, D., and Tversky, A. (2013). "Prospect theory: an analysis of decision under risk," in *Handbook of the Fundamentals of Financial Decision Making: Part I*, eds L. C. MacLean and W. T. Ziemba (World Scientific), 99–127. doi: 10.1142/9789814417358_0006

Karevold, K., Bugge, A. B., Ueland, Ø., Slapø, H. B., Schjøll, A., Rosenlund, T. G., et al. (2017). *From Knowledge to Action: The Behavioral Insights of Food Choices: Influencing Consumer to Eat Healthier*. Oslo. Retrieved from: http://greenudge.org/wp-content/uploads/2018/03/GreeNudge-From-Knowledge-to-Action-report-2017.pdf

King, D., Greaves, F., Vlaev, I., and Darzi, A. (2013). Approaches based on behavioral economics could help nudge patients and providers toward lower health spending growth. *Health Affairs* 32, 661–668. doi: 10.1377/hlthaff.2012.1348

Kiszko, K. M., Martinez, O. D., Abrams, C., and Elbel, B. (2014). The influence of calorie labeling on food orders and consumption: a review of the literature. *J. Commun. Health* 39, 1248–1269. doi: 10.1007/s10900-014-9876-0

Kosters, M., and Van der Heijden, J. (2015). From mechanism to virtue: evaluating Nudge theory. *Evaluation* 21, 276–291. doi: 10.1177/1356389015590218

Krystallis, A., de Barcellos, M. D., Kügler, J. O., Verbeke, W., and Grunert, K. G. (2009). Attitudes of European citizens towards pig production systems. *Livestock Sci.* 126, 46–56. doi: 10.1016/j.livsci.2009.05.016

Long, M. W., Tobias, D. K., Cradock, A. L., Batchelder, H., and Gortmaker, S. L. (2015). Systematic review and meta-analysis of the impact of restaurant menu calorie labeling. *Am. J. Public Health* 105, e11-e24. doi: 10.2105/AJPH.2015.302570

Madhvapaty, H., and DasGupta, A. (2015). A study of food product labelling for products aimed at children. *J. Business Manag.* 17, 88–96. doi: 10.9790/487X-17338896

Marteau, T. M., Ogilvie, D., Roland, M., Suhrcke, M., and Kelly, M. P. (2011). Judging nudging: can nudging improve population health? *Br. Med. J.* 342:d228. doi: 10.1136/bmj.d228

McMichael, A. J., Powels, J. W., Butler, C. D., and Uauy, R. U. (2007). Food, livestock production, energy, climate change and health. *Lancet* 370, 1253–1263. doi: 10.1016/S0140-6736(07)61256-2

Meiselman, H. L., and Bell, R. (2003). Eating habits. *Encycl. Food Sci. Nutr.* 2, 1963–1968. doi: 10.1016/B0-12-227055-X/00379-5

Mitchell, V.-W., Walsh, G., and Yamin, M. (2005). Towards a conceptual model of consumer confusion. *Assoc. Consumer Res.* 32:2005. Available online at: https://pdfs.semanticscholar.org/6373/169e0bb772bfcc554200d30f55195b19a324.pdf

Monahan, T., and Fisher, J. A. (2010). Benefits of 'observer effects': lessons from the field. *Qual. Res.* 10, 357–376. doi: 10.1177/1468794110362874

National Institutes of Health. (2015). *A Compilation of Dietary Supplement Statements. From the Scientific Report of the 2015 Dietary Guidelines Advisory Committee*. Washington, DC. Retrieved from: https://ods.od.nih.gov/About/2015_DGAC_Report.aspx

Nelson, M. E., Hamm, M. W., Hu, F. B., Abrams, S. A., and Griffin, T. S. (2016). Alignment of healthy dietary patterns and environmental sustainability: a systematic review. *Adv. Nutr. Int. Rev. J.* 7, 1005–1025. doi: 10.3945/an.116.012567

Nordic Council of Minsters. (2012). *Nordic Nutrition Recommendations 2012—Integrating Nutrition and Physical Activity*.

Ölander, F., and Thøgersen, J. (2014). Informing versus nudging in environmental policy. *J. Consumer Pol.* 37, 341–356. doi: 10.1007/s10603-014-9256-2

Rothman, R. L., Housam, R., Weiss, H., Davis, D., Gregory, R., Gebretsadik, T., et al. (2006). Patient understanding of food labels: the role of literacy and numeracy. *Am. J. Prevent. Med.* 31, 391–398. doi: 10.1016/j.amepre.2006.07.025

Sabate, J., and Soret, S. (2014). Sustainability of plant-based diets: back to the future. *Am. J. Clin. Nutr.* 100, 476–482. doi: 10.3945/ajcn.113.071522

Scarborough, P., Appleby, P. N., Mizdrak, A., Briggs, A. D. M., Travis, R. C., Bradbury, K. E., et al. (2014). Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. *Clim. Change* 125, 179–192. doi: 10.1007/s10584-014-1169-1

Sharpe, K. M., Staelin, R., and Huber, J. (2008). Using extremeness aversion to fight obesity: policy implications of context dependent demand. *J. Consumer Res.* 35, 406–422. doi: 10.1086/587631

Sinclair, S. E., Cooper, M., and Mansfield, E. D. (2014). The influence of menu labeling on calories selected or consumed: a systematic review and meta-analysis. *J. Acad. Nutr. Diet.* 114, 1375–1388. doi: 10.1016/j.jand.2014.05.014

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., et al. (2018). Options for keeping the food system within environmental limits. *Nature* 562, 519–525. doi: 10.1038/s41586-018-0594-0

Stehfest, E., Bouwman, L., Van Vuuren, D. P., Den Elzen, M. G., Eickhout, B., and Kabat, P. (2009). Climate benefits of changing diet. *Clim. Change* 95, 83–102. doi: 10.1007/s10584-008-9534-6

Steinfeld, H., Costales, A., Rushton, J., Scherf, B., Bennett, T., and Hall, D. (2006). *Underneath the Livestock Revolution Rome, Italy: The 2006 Livestock Report FAO*. Rome: FAO. Retrieved from: ftp://ftp.fao.org/docrep/fao/009/a0255e/a0255e02.pdf

Sunstein, C. R., and Thaler, R. H. (2008). *Nudge: Improving Decisions About Health, Wealth and Happiness*. New Haven: Yale University Press.

Swartz, J. J., Braxton, D., and Viera, A. J. (2011). Calorie menu labeling on quick-service restaurant menus: an updated systematic review of the literature. *Int. J. Behav. Nutr. Phys. Activity* 8:135. doi: 10.1186/1479-5868-8-135

Tang, E., Fryxell, G. E., and Chow, C. S. (2004). Visual and verbal communication in the design of eco-label for green consumer products. *J. Int. Consumer Marketing* 16, 85–105. doi: 10.1300/J046v16n04_05

The Nielsen Company. (2016). *What's in Our Food and on Our Mind Ingredient and Dinning-Out Trends Acround the World.* New York, NY. Retrieved from: https://www.nielsen.com/content/dam/nielsenglobal/eu/docs/pdf/Global%20Ingredient%20and%20Out-of-Home%20Dining%20Trends%20Report.pdf

Thorndike, A. N., Riis, J., Sonnenberg, L. M., and Levy, D. E. (2014). Traffic-light labels and choice architecture: promoting healthy food choices. *Am. J. Prevent. Med.* 46, 143–149. doi: 10.1016/j.amepre.2013.10.002

Thorndike, A. N., Sonnenberg, L., Riis, J., Barraclough, S., and Levy, D. E. (2012). A 2-phase labeling and choice architecture intervention to improve healthy food and beverage choices. *Am. J. Public Health* 102, 527–533. doi: 10.2105/AJPH.2011.300391

Vanclay, J. K., Shortiss, J., Aulsebrook, S., Gillespie, A. M., Howell, B. C., Johanni, R., et al. (2011). Customer response to carbon labelling of groceries. *J. Consumer Pol.* 34, 153–160. doi: 10.1007/s10603-010-9140-7

Variyam, J. N., Blaylock, J., and Smallwood, D. (1995). *Modeling Nutrient Intake: The Role of Dietary Information*. US Department of Agriculture. Economic Research Service.

Vlaeminck, P., Jiang, T., and Vranken, L. (2014). Food labeling and eco-friendly consumption: experimental evidence from a Belgian supermarket. *Ecol. Econ.* 108, 180–190. doi: 10.1016/j.ecolecon.2014.10.019

Weiss, J. A., and Tschirhart, M. (1994). Public information campaigns as policy instruments. *J. Pol. Anal. Manag.* 13, 82–119. doi: 10.2307/3325092

Wills, J. M., genannt Bonsmann, S. S., Kolka, M., and Grunert, K. G. (2012). European consumers and health claims: attitudes, understanding and purchasing behaviour. *Proc. Nutr. Soc.* 71, 229–236. doi: 10.1017/S0029665112000043

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 25 September 2019
doi: 10.3389/fsufs.2019.00076

Advancing an Integrative Framework to Evaluate Sustainability in National Dietary Guidelines

Selena Ahmed[1], *Shauna Downs*[2]* *and Jessica Fanzo*[3]

[1] *Sustainable Food Systems Program, Department of Health and Human Development, Montana State University, Bozeman, MT, United States,* [2] *Department of Urban-Global Public Health, Rutgers School of Public Health, Rutgers University, Newark, NJ, United States,* [3] *Berman Institute of Bioethics and School of Advanced International Studies, Johns Hopkins University, Baltimore, MD, United States*

The food system is responsible for some of society's most pressing sustainability challenges. Dietary guidelines are one policy tool to help address the multiple sustainability challenges associated with food systems through dietary recommendations that better support environmental and human well-being. This article develops and applies a sustainability framework scoring tool comprised of four key dimensions (environmental, economic, human health, and sociocultural and political) and 32 sub-dimensions of sustainable food systems for the analysis and modification of national dietary guidelines. Two coders pilot tested the framework to quantify the occurrence of sustainability dimensions and sub-dimensions in national and regional dietary guidelines of 12 randomly selected high-income and upper-middle income countries including Albania, Australia, Brazil, the Grenadines, Grenada, Qatar, Netherlands, Nordic Countries, St. Vincent, Sweden, Thailand, the United Kingdom, and the United States. Sustainability Dimension Scores (SDS) were calculated as a percentage of the occurrence of the eight sub-dimensions comprising each sustainability dimension and Total Sustainability Scores (TSS) were calculated as a percentage of the occurrence of the 32 sub-dimensions in each guideline. Inter-rater reliability of TSS and SDS indicated high validity of applying the sustainability framework for dietary guidelines. SDS varied between the four sustainability dimensions with human health being the most represented in the dietary guidelines examined, as hypothesized (average SDS score of 83%; range from 50 to 100%). Significant differences ($p < 0.0001$) were found in mean SDS between the four sustainability dimensions. Overall, results indicate that the ecological (average SDS score of 31%; range from 0 to 100%) economic (average SDS score of 29%; range from 0 to 100%), and socio-cultural and political (average SDS score of 44%; range of 0–100%) dimensions of sustainability are underrepresented in the examined national dietary guidelines with significant differences in SDS between guidelines ($p < 0.0001$). TSS varied by country between 12 and 74% with a mean score of 36% (± 20%). Brazil had the highest TSS (74%) followed by Australia (69%). The sustainability framework presented here can be applied by policy makers, researchers, and practitioners to identify gaps and opportunities to modify national dietary guidelines and associated programs for transforming food systems through diets that support planetary health.

Keywords: dietary guidelines, sustainability, sustainable diets, integrative framework, food policy

Edited by:
Carola Strassner,
Münster University of Applied Sciences, Germany

Reviewed by:
Aida Turrini,
Council for Agricultural and Economics Research, Italy
Silvana Moscatelli,
Italian National Research Council (CNR), Italy

***Correspondence:**
Shauna Downs
sd1081@sph.rutgers.edu

Specialty section:
This article was submitted to Nutrition and Sustainable Diets, a section of the journal Frontiers in Sustainable Food Systems

Received: *17 June 2019*
Accepted: *04 September 2019*
Published: *25 September 2019*

Citation:
Ahmed S, Downs S and Fanzo J (2019) Advancing an Integrative Framework to Evaluate Sustainability in National Dietary Guidelines. Front. Sustain. Food Syst. 3:76. doi: 10.3389/fsufs.2019.00076

INTRODUCTION

It is widely recognized that the way humans produce, distribute, consume, and waste food through the food system is responsible for some of society's most pressing sustainability challenges (Horrigan et al., 2002; Gomiero et al., 2011; Edenhofer et al., 2014; Tilman and Clark, 2014; He et al., 2018; Willett et al., 2019). Food systems are composed of complex sub-systems of diverse components, stakeholders, and processes from production to consumption to waste including communities and policies at local, national, and global scales (Herforth et al., 2017; Ahmed and Byker Shanks, 2019). While processes of the food system are linked with numerous environmental externalities, such as climate change, biodiversity loss, and water and air pollution (Vermeulen et al., 2012), human nutrition is critically dependent on multiple ecosystem services including water, soil fertility, pollination, climate regulation, and food quality (Deckelbaum et al., 2006). The sustainability challenges of the food system are exacerbated by climate change and variability (Vermeulen et al., 2012; Wheeler and von Braun, 2013) that threatens food security and public health through decreased agricultural production (Ewert et al., 2005; Avnery et al., 2011a,b; Tai et al., 2014), increased food contamination (Tefera, 2012), disruption of food supply chains (Campbell et al., 2016), increased prices (Tai et al., 2014), and reduced food quality (Myers et al., 2014; Ahmed and Stepp, 2016). The concept of sustainable diets has been promoted in recognition of the complex and interconnected challenges facing food systems (Gussow and Clancy, 1986; Burlingame, 2012).

Sustainable diets are healthy diets from sustainable food systems that advance the human condition and conserve ecological resources in socially acceptable ways (Burlingame, 2012; Johnston et al., 2014; Jones et al., 2016; Ahmed and Byker Shanks, 2019). Four key dimensions of sustainable diets have been identified based on the multiple dimensions of sustainability including ecological, economic, human health, and sociocultural and political (Jones et al., 2016; Downs et al., 2017; Mason and Lang, 2017). The ecological dimension of sustainable diets is characterized by the environmental aspects of agriculture toward minimizing the negative externalities of production while promoting biodiversity and ecosystem services (Nelson et al., 2009). The economic dimension of sustainable diets pertains to the activities and actors along food value chains from farm-to-fork and waste (Garnett, 2011; Barilla Center for Food and Nutrition, 2015; Fanzo et al., 2017). The human health dimension of sustainable diets involves health, nutrition, and food environments and relates to ensuring that diets are holistic and diverse, contain less meat, and are accessible to everyone, including the most vulnerable populations (Jones et al., 2016; Downs et al., 2017; Herforth et al., 2017; Mason and Lang, 2017). The sociocultural and political dimension of sustainable diets takes into account food culture, equity, skills, knowledge, and values as well as broader food system issues including labor rights, animal welfare, and food sovereignty (Downs et al., 2017; Mason and Lang, 2017; Ahmed and Byker Shanks, 2019).

Dietary guidelines are one policy tool that can help address the multiple sustainability challenges associated with diets and food systems through recommendations that better support human nutrition and public health while enhancing the ecological, economic, and cultural aspects of food systems. National dietary guidelines provide a unified voice to the public regarding where the government stands on dietary advice to inform food choices in the context of health promotion and disease prevention (Dietary Guidelines Advisory Committee, 2015). Different national and international institutions as well as scientific organizations have developed dietary guidelines over the past few decades to promote healthy lifestyles aimed at mitigating diet-related chronic disease (Magni et al., 2017). In addition to informing consumers about dietary choices, national dietary guidelines serve as the foundation for information on food and nutrition policies and programs instituted within a country, often with budgetary allocations (Dietary Guidelines Advisory Committee). For example, national dietary guidelines of the United States inform multiple national programs including the formulation of lunches as part of the National School Lunch Program, and the composition of the safety net provided by the Supplemental Nutrition Assistance Program as well as the Women, Infants, and Children (WIC) program. The food and beverage industry often responds to changes proposed in dietary guidelines by reformulating products.

The focus of dietary guidelines in the past was largely based on meeting nutrient requirements regarding how people should eat in their specific socio-ecological contexts to support nutrition and health (Magni et al., 2017). In more recent times, it has been acknowledged that dietary guidelines have the potential to not only support citizens on how to make healthier choices about food (and sometimes about physical activity), they can also serve to guide consumers in a country to make food choices that support the multiple dimensions of sustainable diets (Garnett, 2014; Donini et al., 2016; Nelson et al., 2016). The role of dietary guidelines has broadened in view of the multiple environmental constraints that put pressure on the food system and the resulting need to preserve natural resources and ecosystem health (Fischer and Garnett, 2016; Nelson et al., 2016). For example, several countries including Germany, Brazil, Sweden, and Qatar have incorporated aspects of sustainability into their dietary guidelines in recent years (Fischer and Garnett, 2016). Integrating recommendations for supporting the four dimensions of sustainable diets in national dietary guidelines has the potential to transform the food system toward enhancing planetary health by influencing the food choices and actions of consumers, food and nutrition programs, as well as the food and beverage industry.

The objective of this study was to develop, apply, and validate an integrative framework scoring tool to examine the presence of the environmental, economic, sociocultural/political, and human health dimensions of sustainability and associated sub-dimensions in national dietary guidelines. The goal of applying the integrative framework is to address the following research question: How are environmental, economic, sociocultural/political, and human health dimensions of sustainability and associated sub-dimensions represented in national dietary guidelines and, how does this vary between guidelines? We compared variation of the occurrence of the sustainability dimensions and sub-dimensions between 12 randomly selected national dietary guidelines of high-income and high-middle income countries toward validating the integrative framework for broader application. We hypothesized that the human health dimension of sustainability would be most well-represented in national dietary guidelines compared to the ecological, economic, and socio-cultural and political dimensions of sustainability given the overarching goal of dietary guidelines to improve well-being. In addition, we hypothesized that countries that are recognized to explicitly integrate sustainability into their dietary guidelines would demonstrate greater presence of the ecological, economic, and socio-cultural and political sustainability sub-dimensions. The sustainability framework and findings presented here have the potential to inform the evaluation and modification of national dietary guidelines by pointing to gaps and opportunities regarding the representation of the multiple dimensions of sustainability. Ultimately, taking an integrative sustainability approach to dietary recommendations helps support multiple Sustainable Development Goals (SDGs) toward advancing healthy diets from sustainable food systems that support planetary health.

METHODS

Development of Integrative Sustainability Framework

We developed a sustainability framework tool for quantitatively assessing the four key dimensions of sustainability in national dietary guidelines that was adapted from a previously developed sustainable diets framework published by two of this study's authors (Downs et al., 2017). The previous sustainable diets framework examined food policy in Nepal (Downs et al., 2017). In this study, we drew from this previous study (Downs et al., 2017) along with prevalent constructs of sustainable diets and sustainable food systems described in the literature that are applicable to recommendations in dietary guidelines (**Supplementary Table 1**).

Specifically, the search terms used to identify dimensions of sustainable diets and sustainable food systems that are evidence-based and applicable for inclusion in dietary guidelines included the following: sustainable OR sustainability AND diet OR food OR dietary guidelines. The search terms were entered into multiple publication databases including Web of Science, Science Direct, and Google Scholar. Two coders validated the inclusion of articles resulting from this search. The resulting articles (**Supplementary Table 1**) were scanned to identify specific attributes of sustainable diets and sustainable food systems associated with the environmental, economic, sociocultural/political, and human health dimensions of sustainability. We validated the inclusion of the identified attributes to include as constructs in our integrative framework through a primary literature in multiple publication databases to ensure each construct is supported by evidence.

Based on the resulting evidence in the literature, the study team consisting of experts in sustainable food systems, diets, and nutrition had a discussion regarding the inclusion of the prevalent constructs characterizing sustainable diets and sustainable food systems that are supported by evidence that are applicable to national dietary guidelines. The resulting constructs that are supported by primary evidence were grouped as sub-dimensions of the four ecological, economic, and sociocultural and political, and human health dimensions of sustainability (**Table 1**). In some cases, similar constructs were combined to result in a total of eight sub-dimensions for each dimension of sustainability in the resulting sustainability framework tool (**Table 1**). Additionally, in some cases, specific sub-dimensions of sustainability could potentially be grouped in more than one sustainability dimension due to the interconnectedness of aspects of sustainability. In such cases, we tried to refine the sustainability sub-dimension and its description to be more aligned with a specific sustainability dimension. For example, food security touches upon issues that are connected to human health, economics, and social dimensions of sustainability. We thus broke out the components of food security as nutrition aspects of food security and economic aspects of food security and refined their descriptions.

Selection of Dietary Guidelines

In order to evaluate the applicability of the resulting integrative framework, the study team compiled all national dietary guidelines that are available in English that are either classified as high-income or upper-middle income. A total of 34 national dietary guidelines were identified that are in English from high-income and upper-middle income countries. As the goal of this study was to test the applicability of the framework in evaluating the representation of sustainability in national dietary guidelines, we focused on national dietary guidelines that are available in English as a convenience sample. We further focused on high-income and upper-middle income countries as advancing sustainable diets may not be as equitable or ethical of an approach in low-income country settings because of the prevalence of undernutrition (Milner and Green, 2018). Our sample size of 12 guidelines represents a sample size of 35% of the available ($n = 34$) national dietary guidelines in English from high-income and upper-middle income countries.

The resulting dietary guidelines were grouped into two categories based on their recognition of integrating sustainability in the literature. Specifically, all high-income and middle-income countries in the sample group that were recognized in the literature (Barilla Center for Food and Nutrition, 2015; Monteiro et al., 2015; Seed, 2015) to integrate sustainability were categorized as Group 1 countries and all other dietary guidelines were categorized as Group 2 countries. A total of seven countries that are either high-income or high-middle income that have national or regional dietary guidelines available in English were assigned as Group 1 countries including: Brazil (Monteiro et al., 2015), Qatar (Seed, 2015), Germany (Barilla Center for Food and Nutrition, 2015), Netherlands (Barilla Center for Food and Nutrition, 2015), Sweden (Barilla Center for Food and Nutrition, 2015), United Kingdom (Barilla Center for Food and Nutrition, 2015), and Nordic Countries (Barilla

TABLE 1 | Sustainability framework tool for evaluating national dietary guidelines.

Sustainability dimensions and sub-dimensions	References
ECOLOGICAL DIMENSION	
Production quality: The dietary guidelines support production systems that cultivate for nutritional quality (crop quality).	Welch and Graham, 1999; Graham et al., 2001; Hunter et al., 2011; Rich et al., 2011; Miller and Welch, 2013; Hallström et al., 2018
Adequate production: The dietary guidelines promote adequate food production and agricultural productivity, such as incentives for production.	Boody et al., 2005; Havstad et al., 2007; Swinton et al., 2007; Levidow and Psarikidou, 2011; Govindan, 2018
Biodiversity, agrobiodiversity, and ecosystem services: The dietary guidelines support conservation and maintenance of biodiversity and agrobiodiversity as well as associated ecosystem services.	Costanza et al., 1997; Tilman et al., 2002; Dudgeon et al., 2006; Frison et al., 2006; Swinton et al., 2007; Johns et al., 2013; Eshel et al., 2014; Hanes et al., 2018
Sustainable agriculture: The dietary guidelines support sustainable agricultural practices and sustainable intensification that limit pesticide, herbicide and fertilizer use.	Tilman et al., 2002, 2011; Sarkar et al., 2017; Lal, 2018; Veltman et al., 2018
Local and seasonal foods: The dietary guidelines support the procurement of foods that are in season and are local.	Edwards-Jones, 2010; Kremer and Deliberty, 2011; Cleveland et al., 2014; Macdiarmid, 2014; Esteve-Llorens et al., 2019; Profeta and Hamm, 2019
Clean energy: The dietary guidelines support the use of clean energy and green or sustainable technologies	Kamat, 2007; Copena and Simón, 2018; Ferrer-Martí et al., 2018; López-González et al., 2018; Terrapon-Pfaff et al., 2018a,b; Vergé et al., 2018
Soil, land, and water conservation and protection: The dietary guidelines support the procurement of food in ways that prevent contamination of soil, land, and water resources, such as protecting watersheds from pollutants.	Carpenter et al., 1998; Tscharntke et al., 2005; Ruini et al., 2015; Biagini and Lazzaroni, 2018; Hu et al., 2018; Soteriades et al., 2018; Thorlakson et al., 2018
Low GHGE and climate resilience: The dietary guidelines support production methods with relatively low GHG emissions; designing and managing for agricultural systems for climate change/climate resilience	Lipper et al., 2014; Ruini et al., 2015; Eory et al., 2018; González-García et al., 2018; Leon and Ishihara, 2018; Singh et al., 2018; Vetter et al., 2018; Westermann et al., 2018
ECONOMIC DIMENSION	
Distribution, supply chains, and transport: The dietary guidelines take into account food distribution, supply chains, and transport, such as direct sales between producers and consumers.	Kuo and Chen, 2010; Poppe et al., 2013; Accorsi et al., 2018; Meneghetti et al., 2018; Stellingwerf et al., 2018
Economic aspects of food security: The dietary guidelines recognize the importance of having healthy and recommended foods being affordable to overcome economic barriers of access to safe, nutritious, and desirable foods.	Shreck et al., 2006; Duffey et al., 2010; Carter et al., 2011; Cole and Tembo, 2011; Galhena et al., 2013; Ward et al., 2013; Jones et al., 2016; Martin et al., 2016; High Level Panel, 2017; Jessiman-Perreault and McIntyre, 2017; Dizon and Herforth, 2018
Food loss and waste: The dietary guidelines recommend reducing food waste across the food system from farm through fork.	Thyberg and Tonjes, 2016; Abdelradi, 2018; Bjørn et al., 2018; Edwards et al., 2018; Schanes et al., 2018; Schmidt and Matthies, 2018
Food packaging: The dietary guidelines promote reduced food packaging and recycling.	Khan and Tandon, 2017; Dilkes-Hoffman et al., 2018; Fu et al., 2018; Sánchez-Safont et al., 2018; Song et al., 2018; Venkatesh et al., 2018
Food system livelihoods: The dietary guidelines promote livelihoods to support stakeholders in the food system from on farm and throughout food value chains.	Dupuis and Goodman, 2005; Bravo-Ureta et al., 2006; Price and Leviston, 2014; Sulemana and James, 2014; Lalani et al., 2016; van Dijk et al., 2016
Farmers' markets and local food systems: The dietary guidelines recognize the importance of local food systems including farmers' markets, community supported agriculture (CSA), food cooperatives, and food hubs.	Cone and Myhre, 2000; Hinrichs, 2000; King, 2008; O'Neill, 2014; Forssell and Lankoski, 2015
Food storage and preparation: The dietary guidelines make recommendations to avoid resource-intensive food storage of cold chain items and high-energy preparation, such as the use of a microwave.	Lado and Yousef, 2002; Wood and Newborough, 2003; Canals et al., 2007; Zanoni and Zavanella, 2012; Lelieveld et al., 2015; Li et al., 2017; van Holsteijn and Kemna, 2018
Food advertising: The dietary guidelines recognizes the role of food advertising and marketing on food choices.	Vermeir and Verbeke, 2006; Friedmann, 2007; Dodds et al., 2008; Vogt and Kaiser, 2008; Magnus et al., 2009; Macrae et al., 2012; Grunert et al., 2014; Kemps et al., 2014
HUMAN HEALTH DIMENSION	
Dietary diversity: The dietary guidelines promote dietary diversity to reduce risk of nutrient deficiencies.	Kant et al., 1993; Onyango, 2003; Arimond and Ruel, 2004; Mirmiran et al., 2004; Remans et al., 2014; Berg et al., 2018; Keflie et al., 2018
Regular exercise and physical activity: The dietary guidelines promote physical activity and movement away from sedentary lifestyles.	Pan et al., 1997; Ussher et al., 2007; Barton et al., 2009; Chodzko-Zajko et al., 2009; Melzer et al., 2010; Södergren et al., 2012; Barwais et al., 2013; Tozzi et al., 2016; Edwards and Loprinzi, 2017
Food safety: The dietary guidelines promote food safety to prevent foodborne illness, contamination, negative health influence of agriculture and diseases linked to chemicals and pesticide use.	Lee et al., 2001; Antunes et al., 2003; Lin et al., 2009; Moffatt et al., 2011; Kataoka et al., 2014; Hoelzer et al., 2018; Rivera et al., 2018; van Asselt et al., 2018
Energy limitation: The dietary guidelines promote the limitation of energy/calorie consumption and reduce portion sizes to prevent overweight, obesity, and diet-related non-communicable diseases.	Lowe and Butryn, 2007; Misra et al., 2011; Eyles et al., 2012; Deepika and Vijayakumar, 2017; Popkin and Reardon, 2018

(Continued)

TABLE 1 | Continued

Sustainability dimensions and sub-dimensions	References
Ultra-processed food limitation: The dietary guidelines promote the limitation of ultra-processed foods and food high in added sugars.	Monteiro et al., 2011; Poti et al., 2017; Albuquerque et al., 2018; Juul et al., 2018; Larrick and Mendelsohn, 2018; Schnabel et al., 2018
Plant-based diet and nutrient-dense foods: The dietary guidelines promote plant-based diets of nutrient dense foods, such as fruits, vegetables, and legumes to reduce risk of chronic disease while recommending less consumption of non-lean meat and processed meat including selecting of other non-meat choices of protein.	Pimentel and Pimentel, 2003; Bach-Faig et al., 2011; Tektonidis et al., 2015; Kahleova et al., 2018; Salas-Salvadó et al., 2018; Satija and Hu, 2018
Nutrition aspects of food security: The dietary guidelines promote nutrition aspects of food security including access to sufficient quantity and quality of nutritious foods to meet dietary needs.	Rose and Richards, 2004; Bodor et al., 2008; Caspi et al., 2012; Gittelsohn et al., 2012; Barosh et al., 2014
Holistic diets: The dietary guidelines promote a holistic dietary approach of healthy dietary patterns to meet personal, cultural, and traditional preferences that promote overall health.	Lee et al., 2002; Burgess et al., 2005; Frison et al., 2006; Kwon et al., 2007; Johnson-Down and Egeland, 2010
SOCIO-CULTURAL AND POLITICAL DIMENSION	
Food consciousness: The dietary guidelines recognizes the role of food consciousness, consumer knowledge, and education in supporting healthy and sustainable food choices.	Wilkins, 2005; Fresco, 2009; Mancini et al., 2017; Lazzarini et al., 2018; Lentz et al., 2018
Consumer preferences: The dietary guidelines recognize variation of food choice preferences and desirability of different foods on the basis of cultural history and other socio-cultural factors.	Grunert, 2005; Dawson, 2013; Ellison et al., 2014; Asioli et al., 2017; Kalbar et al., 2018
Equity issues: The dietary guidelines support equity in the food system including on-farm, in market, trade, distribution, food service, and policy sectors.	Browne et al., 2000; Maloni and Brown, 2006; Tregear, 2012; Bacon et al., 2014; Nost, 2014
Food sovereignty: The dietary guidelines support food sovereignty, food rights, food justice, and empowerment.	Dupraz and Postolle, 2013; Chaifetz and Jagger, 2014; Shinn, 2016; Steckley, 2016; Leventon and Laudan, 2017; Wittman et al., 2017
Food knowledge and skills: The dietary guidelines recognize variation of knowledge and skills as related to food cultivation, procurement, purchasing, planning, and preparation.	Hyland et al., 2006; Larson et al., 2006; Hersch et al., 2014; Utter et al., 2016; Romani et al., 2018
Food system and cultural values: The dietary guidelines recognize variation of family, community, and traditional values in the food system.	Kalof et al., 1999; Renzaho et al., 2008; Raymond et al., 2009; D'Sylva and Beagan, 2011; Banna et al., 2016
Labor: The dietary guidelines support safe labor conditions and standards for workers in the food system.	New, 2015; Sbicca, 2015; Hendrickson et al., 2018; Mook and Overdevest, 2018; Oya et al., 2018; Staelens et al., 2018
Animal welfare: The dietary guidelines support healthy, comfortable, well-nourished, and safe conditions for animals raised for livestock.	Edge and Barnett, 2009; Thornton, 2010; Ibarra et al., 2018; Rich et al., 2018; Sonoda et al., 2018

*This framework integrates the four key dimensions of sustainability including the ecological, economic, and socio-cultural/political, and human health dimensions that are each comprised of eight sub-dimensions of sustainability. We developed this framework by combining the prevalent constructs characterizing sustainable diets and sustainable food systems from a literature search that were applicable to national dietary guidelines into the sub-dimensions of the four dimensions of sustainability (**Supplementary Table 1**). We validated the inclusion of the identified constructs through a primary literature to ensure each construct is supported by evidence (listed in the References below).*

Center for Food and Nutrition, 2015). The Nordic Countries include Denmark, Finland, Iceland, Norway, Sweden, as well as the Faroe Islands, Greenland, and Aland. Although Sweden is included in the Nordic Countries' recommendations, given that they have their own standalone dietary guidelines they have been treated separately in Group 1. We assigned each country a number and used a random number generator to randomly select six dietary guidelines in the Group 1 category and six countries from the Group 2 category. A sample size of 12 national dietary guidelines consisting of six guidelines from Group 1 countries and six guidelines from Group 2 countries was based on a feasible number of guidelines to evaluate by the study team while having relevant power to pilot test the integrative sustainability framework and the research question regarding variation of sustainability dimensions between dietary guidelines of Group 1 and Group 2 countries. The randomly selected Group 1 countries were: Brazil, Qatar, Netherlands, Sweden, the United Kingdom, and Nordic Countries (Barilla Center for Food and Nutrition, 2015; Monteiro et al., 2015; Seed, 2015). The randomly selected Group 2 countries were: Grenada, Albania, Australia, United States, Thailand, and St. Vincent and the Grenadines. The most current dietary guidelines available in 2017 were used for this study.

Evaluation of Dietary Guidelines

Two coders applied the sustainability framework tool to score each dietary guideline in the study. For each of the 32 sub-dimensions in the sustainability framework (**Table 1**), the coder assigned a 0 for the absence of the sub-dimension in the dietary guidelines and a 1 to indicate the presence of the sub-dimension. The coder further listed the page number(s) which each sub-dimension theme was present in national dietary guidelines as well as highlighted the specific text. Discrepancies between coders were resolved through discussion and support by a third coder where each guideline was revisited and the associated text was discussed.

Data Analysis

We created two scoring indices to evaluate the representation of sustainability dimensions and sub-dimensions in national dietary guidelines. Sustainability Dimension Scores (SDS) of each of the four dimensions of sustainability were calculated as a percentage by tabulating the total presence of the associated eight sub-dimensions of sustainability. Total Sustainability Scores (TSS) were calculated as a percentage by calculating the presence of the 32 sub-dimensions in each guideline. JMP (version 13.0 SAS Institute Inc., Cary, NC) was used for measuring interrater reliability of coded results, statistical analysis, for and creating graphs. Specifically, Analysis of Variance (ANOVA) and pairwise comparison tests were applied to examine differences in means of TSS and SDS between the sustainability dimensions and between the national dietary guidelines.

RESULTS

Literature Search Outcomes

A total of 101 articles resulted from the literature search on sustainable diets, sustainable food systems, and sustainability in dietary guidelines that were considered suitable by the study team to examine for attributes to include in the integrative framework for evaluating dietary guidelines. The resulting sub-dimensions included in the framework either relate to those being managed by individuals, such as through dietary choices, those that relate to systems-level management by policy makers and institutions, or those that are influenced by both individual and systems-level management. For the ecological dimension of sustainability, the sub-dimensions of production quality and adequate production are managed at the systems level while food procurement that supports the following ecological sub-dimensions of sustainability are influenced by both systems-level and individual choices: biodiversity, agrobiodiversity, and ecosystem services; sustainable agriculture; local and seasonal foods; clean energy; low GHGE and climate resilience. For the economic dimension of sustainability, the following sub-dimensions are managed at the systems level: distribution, supply chains, and transport; economic aspects of food security; food system livelihoods; and food advertising. Food procurement that supports food loss and waste; food packaging; farmers' markets and local food systems; and food storage and preparation are influenced by both systems-level and individual choices for the economic dimension of sustainability. For the human health dimension of sustainability, the sub-dimensions of food safety as well as nutrition aspects of food security are managed at the systems scale while dietary diversity; regular exercise and physical activity; energy limitation; ultra-processed food limitation; plant-based diets and nutrient-dense foods; and holistic diets are influenced at both individual and systems levels. For the sociocultural/political dimension of sustainability, the attributes of food consciousness, consumer preferences, and food knowledge and skills are those related to individual dietary choice while equity issues, food sovereignty, labor, and animal welfare are those related to the systems level of policy and institutions. Food systems and cultural values are influenced by both the individual and systems levels.

Variation of Sustainability Dimension Scores (SDS)

Inter-rater reliability of Total Sustainability Scores (TSS) and Sustainability Dimension Scores (SDS) indicated high validity of applying the sustainability framework for national dietary guidelines. Application of the sustainability framework tool (**Table 1**) for presence of sustainability dimensions found Sustainability Dimension Scores (SDS) varied between the four sustainability dimensions (**Figure 1**) with human health being the most represented dimension in the national dietary guidelines examined (average SDS score of 83%; range from 50 to 100%). Overall, results indicate that the ecological (average SDS score of 31%) economic (average SDS score of 29%; range from 0 to 100%), and socio-cultural and political (average SDS score of 44%; range of 0–100%) dimensions of sustainability are underrepresented in national dietary guidelines. Significant differences ($p < 0.0001$) were found in means SDS between the four sustainability dimensions. Pair-wise comparison between the four sustainability dimensions demonstrates that the mean SDS of the human health dimension was significantly higher ($p < 0.0001$) than that of the economic, ecological, and sociocultural and political dimensions. No significant differences in means of SDS were found between these latter three sustainability dimensions ($p > 0.05$).

For the ecological dimension of sustainability (**Figure 2**), the most represented sub-dimensions were local and seasonal foods (present in 50% of the dietary guidelines) followed by sustainable agriculture practices and production quality (each present in 33% of the dietary guidelines). The least represented sub-dimension for the ecological dimension of sustainability was clean energy and sustainable technologies (present in 17% of the dietary guidelines). The SDS for the ecological dimension of sustainability ranged from 0 to 100% between national dietary guidelines with significant differences between national dietary guidelines ($p < 0.0001$); the dietary guidelines of Brazil (SDS of 100%), Nordic Countries (88%), Australia (88%), and Sweden (50%) had the highest scores. Average SDS for the ecological dimension of sustainability of Group 1 countries that are recognized to integrate sustainability in dietary guidelines in the literature was 33% and 31% for Group 2 countries; this difference was not significant ($p = 0.94$).

For the economic dimension of sustainability (**Figure 3**), the most represented sub-dimensions were food advertising (present in 42% of the dietary guidelines) followed by costs of diets, food loss and food waste, and food packaging and recycling (each present in 33% of the dietary guidelines). The least represented sub-dimension for the economic dimension of sustainability was distribution, supply chains, and transport (absent in all of the dietary guidelines). The SDS for the economic dimension of sustainability ranged from 0 to 100% with significant differences between national dietary guidelines ($p < 0.0001$); Australia (SDS of 100%), Brazil (88%), and Qatar (50%) had the highest scores. Average SDS for the economic dimension of sustainability of Group 1 countries was 38 and 23% for Group 2 countries; this difference was not significant ($p > 0.50$).

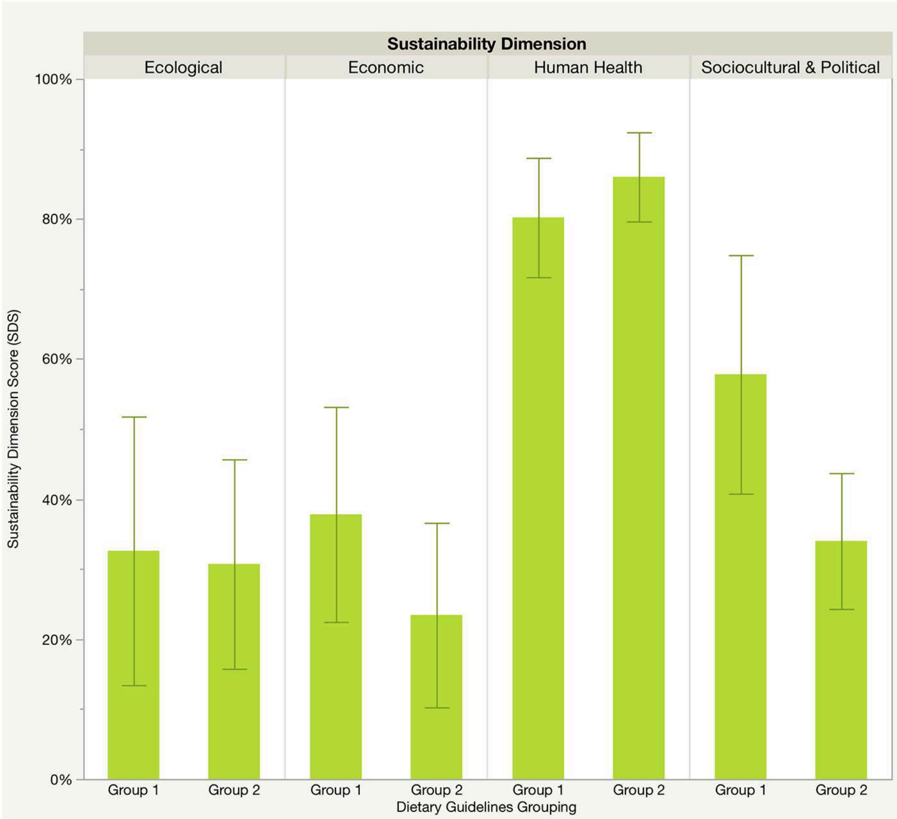


FIGURE 1 | Variation of sustainability dimension scores (SDS) between ecological, economic, human health, and socio-cultural and political sustainability in national dietary guidelines. Application of the sustainability framework tool (**Table 1**) for presence of sustainability dimensions found sustainability dimension scores (SDS) varied between the four sustainability dimensions with human health being the most represented dimension in the national dietary guidelines examined. Overall, results indicate that the ecological, economic, and socio-cultural and political dimensions of sustainability are underrepresented in national dietary guidelines. Significant differences ($p < 0.0001$) were found in means SDS between the four sustainability dimensions. Pair-wise comparison between the four sustainability dimensions demonstrates that the mean SDS of the human health dimension was significantly higher ($p < 0.0001$) than that of the economic, ecological, and sociocultural and political dimensions. No significant differences in means of SDS were found between these latter three sustainability dimensions ($p > 0.05$). There were no significant differences in the SDS for the dimensions of sustainability between Group 1 countries that are recognized in the literature to integrate sustainability in dietary guidelines compared to Group 2 countries.

For the human health dimension of sustainability (**Figure 4**), dietary diversity, ultra-processed food limitation, and plant-based diets were present in all of the dietary guidelines examined. Regular exercise and physical activity (present in 92% of the dietary guidelines), energy limitation (92% prevalence), and holistic diets (75% prevalence) were other prevalent sub-dimensions of the human health dimension of sustainability. The least represented sub-dimension for the human health of sustainability was nutrition aspects of food security related to food environments (present in 42% of the dietary guidelines). The SDS for the human health dimension of sustainability ranged from 50 to 100% without significant differences between national dietary guidelines ($p = 0.06$). The dietary guidelines of Brazil, Australia, and the United States all had the presence of all human health sustainability sub-dimensions. The other dietary guidelines examined also had high SDS for the human health dimension of sustainability including 88% each for Qatar, Sweden, Nordic Countries, Grenada, Albania, and Thailand. Average SDS for the human health dimension of sustainability of Group 1 countries was 80% and 86% for Group 2 countries; this difference was not significant ($p = 0.59$).

For the socio-cultural and political dimension of sustainability (**Figure 5**), the most represented sub-dimensions were food consciousness (present in 83% of the dietary guidelines) followed by food knowledge and skills and food system and cultural values (both present in 58% of the dietary guidelines). The least represented sub-dimension for the socio-cultural and political dimension of sustainability was labor (present in 17% of the dietary guidelines). The SDS for the socio-cultural and political dimension of sustainability ranged from 0 to 100% with significant differences between national dietary guidelines ($p < 0.0001$); Brazil (SDS of 100%), Qatar (88%), and Australia (88%) had the highest scores. Average SDS socio-cultural and political dimension of sustainability of Group 1 countries was 58% and 34% for Group 2 countries; this difference was not significant ($p = 0.22$).

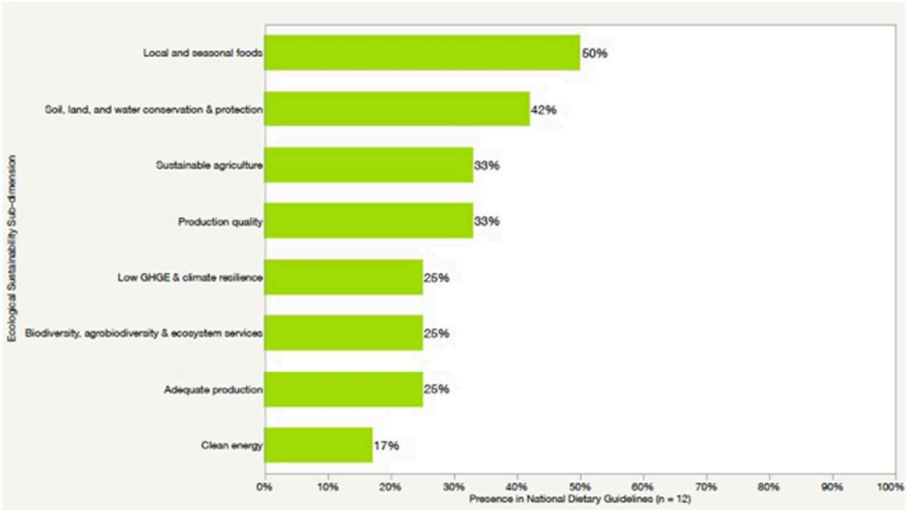


FIGURE 2 | Presence of ecological sub-dimensions in national dietary guidelines. This figure demonstrates the presence of the eight sub-dimensions of ecological sustainability in the 12 national dietary guidelines evaluated in this study.

Variation of Total Sustainability Scores (TSS)

Total Sustainability Scores (TSS) varied by dietary guidelines of the different countries between 12 and 74% with a mean score of 36% (**Figure 6**). Brazil had the highest TSS (74%) followed by Australia (69%). All other dietary guidelines had TSS <50%. Comparison of Group 1 countries (that are recognized in the literature to integrate sustainability in dietary guidelines) with Group 2 countries found that while Group 1 countries overall had higher TSS (39%) than Group 2 countries (33%), this difference was not significant ($p = 0.59$; **Figure 7**). Of note, Australia was categorized as a Group 2 country but had the second highest TSS in this study following Brazil.

DISCUSSION

This study applied and validated a sustainability framework tool to examine national dietary guidelines based on the ecological, economic, sociocultural/political, and human health dimensions of sustainability. The inter-rater reliability of Total Sustainability Scores (TSS) and Sustainability Dimension Scores (SDS) across coders highlights the validity of applying the sustainability framework for evaluating dietary guidelines. Overall, findings demonstrate notable variation in the presence of the multiple sub-dimensions of sustainability in national dietary guidelines of high- and upper-middle income countries with TSS ranging from 12 to 74% and a mean TSS of 36%. Significant differences were further found in mean SDS between the ecological, economic, sociocultural/political, and human health dimensions of sustainability. For the limited sample size of 12 national dietary guidelines from high- and upper-middle income countries analyzed in this study, findings confirm the hypothesis that the human health dimension of sustainability is well-represented while the ecological, economic, and socio-cultural and political dimensions of sustainability are underrepresented, with several exceptions. This finding supports the overarching goal of dietary guidelines which has been to support human health (Magni et al., 2017). More recently, dietary guidelines have been recognized to have the potential to also support the multiple dimensions of sustainable diets (Garnett, 2014; Donini et al., 2016; Nelson et al., 2016). However, our findings did not support the hypothesis that countries that are recognized to explicitly integrate sustainability into their dietary guidelines demonstrate greater presence of the ecological, economic, and socio-cultural and political sustainability sub-dimensions. Policy makers, researchers, and practitioners can apply the sustainability framework presented here to analyze existing guidelines with the view to identifying sustainability gaps and opportunities that can be addressed in future iterations of the guidelines toward supporting both human and planetary health.

Advancing an integrative sustainability framework through national dietary guidelines recognizes the interrelationship of sustainability challenges and opportunities toward meeting multiple Sustainable Development Goals (Global Panel, 2017; Sabbahi et al., 2018; Ahmed and Byker Shanks, 2019). As the current world population of over 7.6 billion is projected to notably increase to 9.3 billion by 2050 (Food and Agriculture Organization, 2009), there is a need for production systems to supply increased levels of food (Alexandratos and Bruinsma, 2012). The increased production of this food should be cultivated in ways that support biodiversity and don't burden ecosystems (Foley et al., 2011; West et al., 2014) while mitigating greenhouse gas emissions (Intergovernmental Panel in Climate Change, 2013; Intergovernmental Panel on Climate Changes, 2014). Concurrently, this food should be produced, distributed, and consumed in ways that recognize the importance of socio-cultural factors in the food system. Inequality in access is a pressing social challenge facing current diets

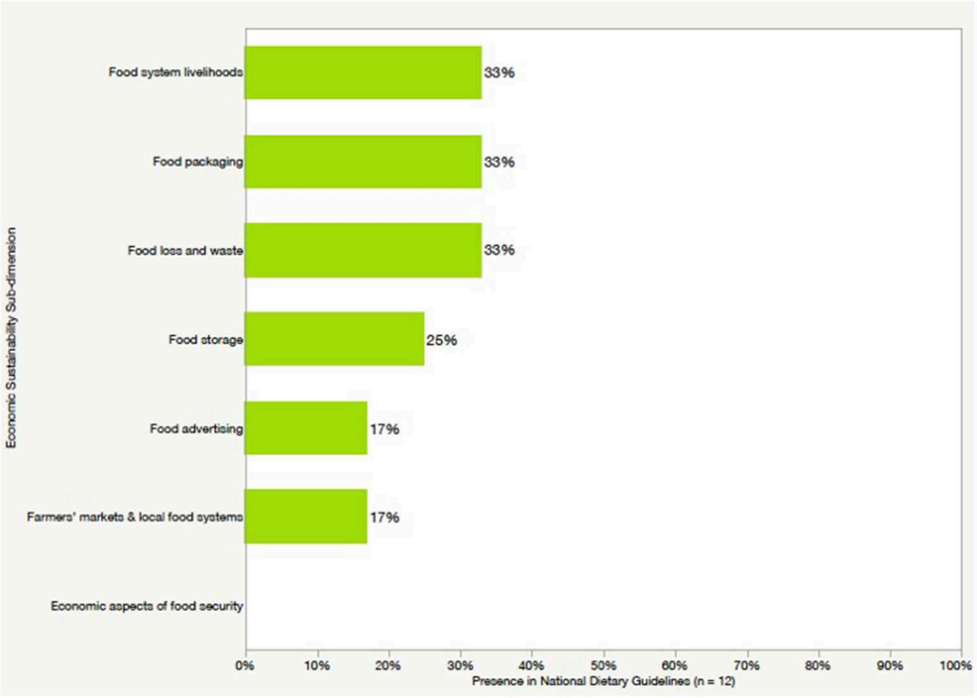


FIGURE 3 | Presence of economic sub-dimensions in national dietary guidelines. This figure demonstrates the presence of the eight sub-dimensions of economic sustainability in the 12 national dietary guidelines evaluated in this study.

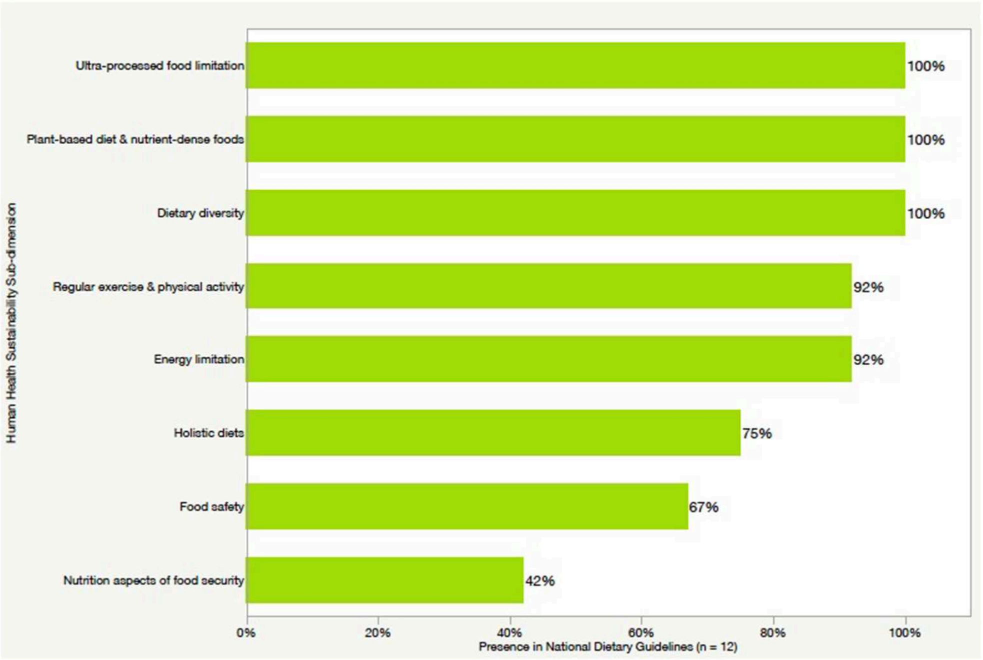


FIGURE 4 | Presence of human health sub-dimensions in national dietary guidelines. This figure demonstrates the presence of the eight sub-dimensions of human health sustainability in the 12 national dietary guidelines evaluated in this study.

that is directly linked to health disparities among vulnerable populations including the lowest income and marginalized groups (Alesina and Glaeser, 2004). Ultimately, taking an integrative sustainability approach to dietary recommendations helps support multiple Sustainable Development Goals (SDGs), such as ending hunger, achieving food security, improving

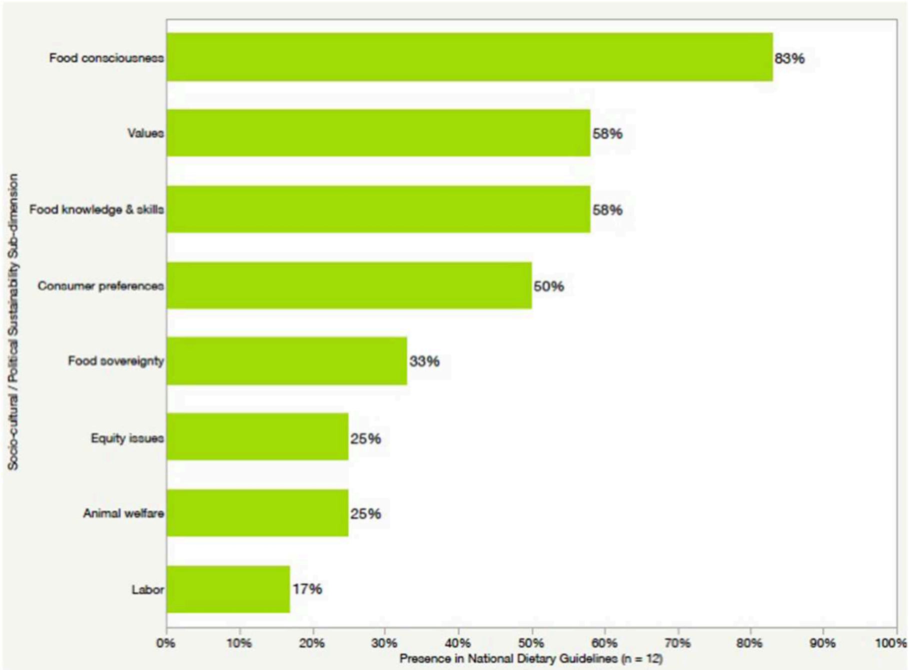


FIGURE 5 | Presence of socio-cultural and political sub-dimensions in national dietary guidelines. This figure demonstrates the presence of the eight sub-dimensions of socio-cultural and political sustainability in the 12 national dietary guidelines evaluated in this study.

nutrition, and promoting sustainable agriculture (SDG 2); promoting well-being for all (SDG 3); reducing poverty (SDG 1); addressing inequality (SDGs 5 and 10); improved work and productivity (SDG 8); and addressing consumption, waste, the effects of climate change, and the use of natural resources (SDGs 12, 13, 14, and 15) (Sabbahi et al., 2018; Ahmed and Byker Shanks, 2019). While these SDGs are being prioritized by international organizations and national governments, they often compete with each other as well as other societal goals.

Our results regarding the general underrepresentation of the ecological, economic, and socio-cultural and political dimensions of sustainability highlight a need to expand the integration of multiple sub-dimensions of sustainability in national dietary guidelines while suggesting complexity of managing multiple dimensions of sustainability (Tuomisto, 2019) including their tradeoffs. For example, previous research has highlighted that the global supply of fruits and vegetables is insufficient to meet health needs based consumption recommendations of national dietary guidelines (Siegel et al., 2014). Another disconnect between dietary recommendations to support human health and food production practices that support environmental health are recommendations of increased fish consumption; if consumers were to increase their fish intake to meet current dietary recommendations, already fragile fish stocks would feel notable pressure (Jenkins et al., 2009). Many of the sub-dimensions of the ecological, economic, and socio-cultural dimensions of sustainability have historically been viewed as being beyond the remit of dietary guidelines and thus explain the numerous gaps seen in the prevalence of these dimensions of sustainability in this study (Fischer and Garnett, 2016; Medact and Eating Better Alliance Policy Briefing, 2017). However, as the linkages between the multiple dimensions of sustainability are recognized as being crucial to planetary health, there is a need for a paradigm shift in the way we approach dietary recommendations toward examining diets within sustainable food systems that support planetary health (Fischer and Garnett, 2016).

While the human health dimension is overall very well-represented in the examined national dietary guidelines, the gap that can be addressed for modifying future dietary guidelines and associated programs is the integration of food security and access. Nutrition aspects of food security linked to food environments was the only human health sub-dimension prevalent in <50% of the dietary guidelines examined. Given that the food environment is a key determinant of healthy diets by shaping consumer interactions in the food system and subsequent food purchases based on the availability, affordability, convenience and desirability of food (Herforth and Ahmed, 2015), dietary guidelines should incorporate an understanding of how key aspects of the food environment influence food security, food access, and diets.

The evaluation of multiple sub-dimensions of sustainability included in the framework presented here can help identify possible unintended consequences of implementing specific recommendations for supporting sustainable diets. Future research is called for to evaluate the suitability of the proposed framework for evaluating dietary guidelines of low-income countries. In advocating for the modification of dietary guidelines that more comprehensively integrate sustainability,

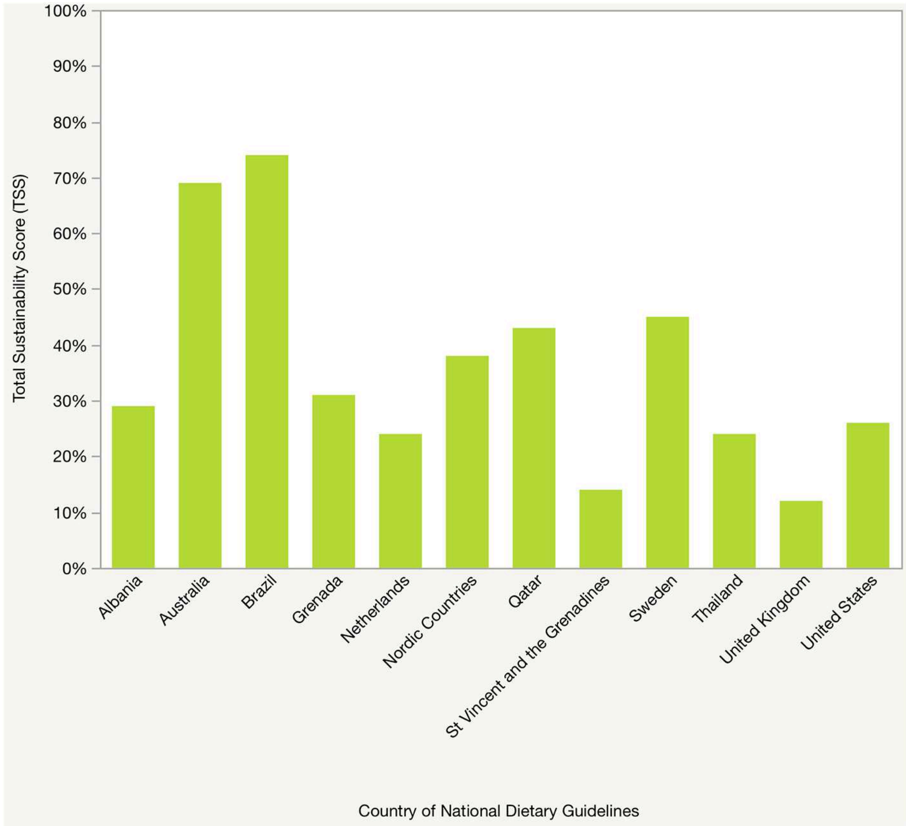


FIGURE 6 | Variation of total sustainability dimension scores (TSS) between national dietary guidelines. This figure demonstrates the variation of total sustainability dimension scores comprised of the 32 sub-dimensions of sustainability in the 12 national dietary guidelines evaluated in this study.

it is important to note the multiple tradeoffs and challenges that exist which call for modification of national dietary guidelines on the basis of local contexts. In addition, after sustainability gaps are identified, the next step is to translate these recommendations into practice by identifying context-specific and effective ways of implementing the required changes for food systems transformation. The 32 sub-dimensions of sustainability that were included in the framework emphasize management decisions at various scales of influence that call for associated interventions and programs at different scales. These scales of influence range from those at the individual level, such as through dietary choices to those at the systems level including those influenced by policy makers and the private sector, as well as those influenced by multiple scales of management.

In advocating for the modification of dietary guidelines that more comprehensively integrate sustainability, it is important to note the multiple challenges that exist. One such challenge is the contentious nature of sustainability in some socio-political contexts. For example, the integration of dimensions of sustainability has been contentious or considered beyond the scope of dietary guidelines in the United States and Australia (Fischer and Garnett, 2016; Medact and Eating Better Alliance Policy Briefing, 2017). While the development of the 2015–20 Dietary Guidelines for Americans considered taking into account sustainability dimensions, sustainability recommendations were ultimately considered beyond the scope of the guidelines due to opposition from agriculture departments and vested interest groups (Medact and Eating Better Alliance Policy Briefing, 2017). However, as demonstrated in this study, even countries that do not explicitly indicate the integration of sustainability into their guidelines, such as Australia can integrate sustainability less explicitly. While Group 1 countries that are recognized in the literature to integrate sustainability in their dietary guidelines had higher SDS for the ecological, economic, and socio-cultural and political dimensions of sustainability compared to Group 2, these differences were not significant. In addition, while Brazil, classified as a Group 1 country in this study had the highest TSS, there were no significant differences in the TSS between Group 1 and Group 2 countries. Despite sustainability being contentious within the Australian national dietary guidelines context, the Australian guidelines had the second highest overall Total Sustainability Scores (TSS) in this study following Brazil. This suggests that countries don't necessarily need to frame their guidelines as "sustainable" in order to include key aspects of sustainability within them. Moreover, those countries that do frame their guidelines as being "sustainable" may only focus on a few aspects of sustainability rather than adopting a more holistic approach. As consumers increasingly expand their

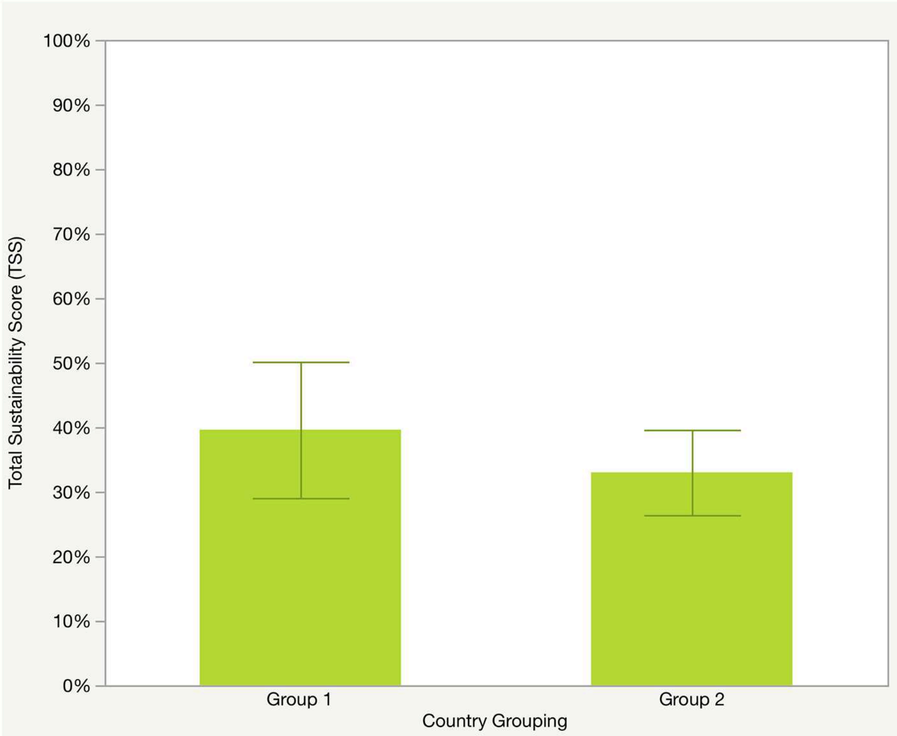


FIGURE 7 | Variation of total sustainability dimension scores (TSS) of national dietary guidelines between country groupings. This figure demonstrates the variation of total sustainability dimension scores comprised of the 32 sub-dimensions of sustainability between countries classified as Group 1 (recognized in the literature to integrate sustainability in dietary guidelines) compared to Group 2. Analysis of variance of TSS between Group 1 and Group 2 found no significant differences.

literacy and values regarding sustainability, the incorporation of sustainability in dietary guidelines will likely increase. A national survey found that 74% of people surveyed in the US agreed that dietary guidelines should include measures of sustainability (John Hopkins Center, 2016). One approach of further increasing sustainability literacy and values is through various curriculum programs targeted at a range of age groups as well as through labeling and advertising.

Another challenge of integrating the multiple dimensions of sustainability in national dietary guidelines is to ensure that associated recommendations and strategies are context specific to a given nation (Tuomisto, 2019) and its' environmental, economic, and socio-cultural factors (Milner and Green, 2018; Springmann et al., 2018) while being applicable to the population as a whole. This requires specific plans and programs associated with the sub-dimensions of sustainability within dietary recommendations to be context-specific to a nation yet applicable and modifiable to the broad population of that nation. For example, recommendations of reducing consumption of animal-source foods in low-income countries may not be as an equitable or ethical of an approach as in high-income country settings because of the prevalence of undernutrition in the former (Milner and Green, 2018). Implementation of a specific approach to sustainable diets may have different implications in different regions (Milner and Green, 2018). Previous research has shown that substituting animal-source foods with plant-based foods has brought greater benefits for health and reductions in emissions of greenhouse gases in high-income countries while being negated at a global level by water use (Springmann et al., 2018). Thus, strategies are called for to support populations to consume recommended foods and amounts within the contextual constraints faced by these populations within a specific nation. For example, recommendations for adopting nutritionally balanced, low animal-source food diets that allow for dietary diversity may be a more equitable approach in low-income countries (Springmann et al., 2018). As the gap between the rich and the poor continues to widen in many countries throughout the world, a more comprehensive approach to addressing this challenge in dietary guidelines will especially be necessary.

Another challenge of integrating multiple dimensions of sustainability in dietary guidelines relates to the number of government ministries and organizations that influence a nation's food system. Although it is often the Ministry of Health who spearheads the development of national dietary guidelines, integrating multiple dimensions of sustainability within guidelines will necessitate the involvement of ministries beyond health and include multi-sectoral collaborations. Ensuring that key stakeholders from ministries and sectors influencing food systems, such as agriculture, trade, etc. are included as part of the co-development of the guidelines will likely help to increase buy-in and improve policy coherence (Milner and Green, 2018; Tuomisto, 2019).

Identifying sustainability gaps in dietary guidelines is one step toward enhancing integrating multiple dimensions of sustainability for transforming food systems. The next step is to translate national dietary recommendations based on specific sub-dimensions of sustainability into practice through programs and plans. These programs and plans should be context-specific and can vary throughout a nation depending on ecological, sociocultural, and economic aspects of a place (Milner and Green, 2018). For example, arable farming may not be possible in certain areas within a country with cattle grazing being the most suitable option for food production (Tuomisto, 2019). Suggestions of primarily plant-based diets in those areas may compromise environmental, socio-cultural, health, and economic aspects of sustainability through import of foods to meet dietary recommendations (Tuomisto, 2019) that are not aligned with cultural preferences and historical diets. Programs would be needed in such areas to educate populations about the about preparation of nutritionally adequate plant-based diets (Tuomisto, 2019).

It is increasingly recognized that enhancing sustainability in food systems is shared by all players in the food system and strategies are needed to ensure the long-term commitment by all concerned parties (Food and Agriculture Organization, 2002). Thus, the development and implementation of programs and plans to support sub-dimensions of sustainability are to target different scales of management including individual-level management, systems-level management by policy makers and institutions, and a combination of individual and systems-level management. As consumers can be powerful forces to direct the market place to provide access to specific foods (Food and Agriculture Organization, 2002) associated with sustainable diets, educational efforts are called for to enhance consumer awareness regarding the sub-dimensions of sustainability that are influenced at the individual scale. At the systems-level, different programs and plans are also called for that address the different scales of food systems including the local, regional, national, and global.

Future research is called for to build upon the integrative framework proposed in this study while addressing multiple limitations of the research presented here. A methodological limitation of the integrative framework we applied in this study was that it coded for the presence and absence of specific sub-dimensions of sustainability and did not evaluate frequency or high vs. low presence of specific sub-dimensions within national dietary guidelines. Our experience in coding indicated notable variation in the frequency of occurrence of a specific sub-dimension of sustainability between dietary guidelines. While some guidelines reiterated the importance of a specific sub-dimension multiple times with extensive supporting information, other guidelines only once briefly touched upon the sub-dimension. For example, the dietary guidelines for Brazil mentioned the importance of procuring seasonal and local foods on multiple pages and in multiple contexts while the guidelines of several other countries, such as Grenada mentioned this sub-dimension of sustainability to a notably lesser extent. However, both scored the same based on the scoring system implemented in this study, yet we can assume that reiterating the importance of a specific sub-dimension multiple times with substantial supporting evidence or recommendations would have greater impact on consumers and the development of supporting programs and policies. Further methodological development is needed in order to systematically evaluate the frequency of the presence of specific sub-dimensions in dietary guidelines. Another limitation of the integrative framework presented here is the equal prioritization of the ecological, economic, socio-cultural/political, and human health dimensions and sub-dimensions of sustainability. Countries implementing national dietary guidelines may have different priorities and can modify the proposed framework and its scoring based on these priorities. Finally, other key limitations of this study were inclusion of dietary guidelines from only upper-middle and high-income countries as well as those available in English. Future analysis of dietary guidelines is called for that applies the integrative approach presented here to include a more representative sample inclusive of low- and middle- income countries as well as in order to identify global patterns and making broader conclusions toward supporting sustainable food systems for all. Further cross-cultural comparison across countries as well as those of different income levels may result in modification of the proposed integrative framework as well as prioritization of the different sub-dimensions of sustainability based on context. The integrative framework and associated scoring indices of Sustainability Dimension Scores and Total Sustainability Scores presented here can further be modified and validated for application for evaluating specific foods (**Supplementary Table 2**), diets (**Supplementary Table 3**), and food environments (**Supplementary Table 4**). This would enable research to evaluate how dietary guidelines of a specific nation translate into impacting local food environments, food availability, and diets.

CONCLUSION

National dietary guidelines are a policy tool that have the potential to shift consumption patterns in directions that support multiple dimensions of sustainability in the food system, while supporting both environmental and human well-being. Given the pressure that food system processes from production through consumption and waste are placing on the planet, coupled with the uncertainty of climate change and variability for food security of a growing population, it is especially critical for food policies, such as national dietary guidelines to support sustainability goals. Effective incorporation of multiple dimensions of sustainability into dietary guidelines has the potential for food system transformation that enables consumers to make food choices that support planetary health.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the manuscript/**Supplementary Files**.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's concept, design, and research questions. SA and SD conducted the data analysis, interpretation, and drafted the manuscript. All authors approved of the final manuscript.

FUNDING

Funding support was provided by the Canadian Institutes of Health Research Postdoctoral Fellowship Award, the United States National Science Foundation (NSF EPSCoR Research Infrastructure Improvement Program Track-2 FEC 1632810), and the United States National Institutes of Health (through Montana IDeA Network for Biomedical Research Excellence NIH NIGMS 5P20GM103474-18; and the Center for American Indian and Rural Health Equity at Montana State University NIH NIGMS 5P20GM1044-17). The content was solely the responsibility of the authors and does not necessarily represent the official views of the Canadian Institutes of Health, the United States National Science Foundation, and the United States National Institutes of Health.

ACKNOWLEDGMENTS

We were grateful to the Research Associates of the Montana State University Food and Health Lab who contributed to the literature search and compilation of data including Erin Smith and Teresa Warne.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2019.00076/full#supplementary-material

REFERENCES

Abdelradi, F. (2018). Food waste behaviour at the household level: a conceptual framework. *Waste Manag.* 71, 485–493. doi: 10.1016/j.wasman.2017.10.001

Accorsi, R., Cholette, S., Manzini, R., and Tufano, A. (2018). A hierarchical data architecture for sustainable food supply chain management and planning. *J. Clean. Product.* 203, 1039–1054. doi: 10.1016/j.jclepro.2018.08.275

Ahmed, S., and Byker Shanks, C. (2019). "Supporting sustainable development goals through sustainable diets," in *Encyclopedia of the UN Sustainable Development Goals. Good Health and Well-Being*, eds W. Leal, T. Wall, A. M. Azul, L. Brandli, P. G. Özuyar (Springer Nature), 696–708. doi: 10.1007/978-3-319-69627-0_101-1

Ahmed, S., and Stepp, J. R. (2016). Beyond yields: climate change effects on specialty crop quality and agroecological management. *Elem. Sci. Anth.* 4:000092. doi: 10.12952/journal.elementa.000092

Albuquerque, T. G., Santos, J., Silva, M. A., Oliveira, M. Beatriz. P. P., and Costa, H. S. (2018). An update on processed foods: Relationship between salt, saturated and trans fatty acids contents. *Food Chem.* 267, 75–82. doi: 10.1016/j.foodchem.2018.01.029

Alesina, A., and Glaeser, E. (2004). *Fighting Poverty in the US and Europe: A World of Difference*. Oxford, UK: Oxford University Press.

Alexandratos, N., and Bruinsma, J. (2012). *World Agriculture Towards 2030/2050: The 2012 Revision* (Rome), 154.

Antunes, P., Réu, C., Sousa, J. C., Peixe, L., and Pestana, N. (2003). Incidence of Salmonella from poultry products and their susceptibility to antimicrobial agents. *Int. J. Food Microbiol.* 82, 97–103. doi: 10.1016/S0168-1605(02)00251-9

Arimond, M., and Ruel, M. T. (2004). Dietary diversity is associated with child nutritional status: evidence from 11 demographic and health surveys. *J. Nutr.* 134, 2579–2585. doi: 10.1093/jn/134.10.2579

Asioli, D., Aschemann-Witzel, J., Caputo, V., Vecchio, R., Annunziata, A., Næs, T., et al. (2017). Making sense of the 'clean label' trends: a review of consumer food choice behavior and discussion of industry implications. *Food Res. Int.* 99, 58–71. doi: 10.1016/j.foodres.2017.07.022

Avnery, S., Mauzerall, D. L., Liu, J., and Horowitz, L. W. (2011a). Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmos. Environ.* 45, 2284–2296. doi: 10.1016/j.atmosenv.2010.11.045

Avnery, S., Mauzerall, D. L., Liu, J., and Horowitz, L. W. (2011b). Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O3 pollution. *Atmos. Environ.* 45, 2297–2309. doi: 10.1016/j.atmosenv.2011.01.002

Bach-Faig, A., Berry, E. M., Lairon, D., Reguant, J., Trichopoulou, A., Dernini, S., et al. (2011). Mediterranean diet pyramid today. Science and cultural updates. *Public Health Nutr.* 14, 2274–2284. doi: 10.1017/S1368980011002515

Bacon, C. M., Sundstrom, W. A., Gómez, M. E. F., Méndez, V. E., Santos, R., Goldoftas, B., et al. (2014). Explaining the 'hungry farmer paradox': smallholders and fair trade cooperatives navigate seasonality and change in Nicaragua's corn and coffee markets. *Global Environ. Change* 25, 133–149. doi: 10.1016/j.gloenvcha.2014.02.005

Banna, J., Gilliland, B., Keefe, M., and Zheng, D. (2016). Cross-cultural comparison of perspectives on healthy eating among Chinese and American undergraduate students. *BMC Public Health* 16:1015. doi: 10.1186/s12889-016-3680-y

Barilla Center for Food and Nutrition (2015). *Double Pyramid 2015 Recommendations for a Sustainable Diet*. Available online at: https://www.barillacfn.com/m/publications/dp-2015-en.pdf (accessed June 13, 2019).

Barosh, L., Friel, S., Engelhardt, K., and Chan, L. (2014). The cost of a healthy and sustainable diet–who can afford it? *Aust. N. Z. J. Public Health* 38, 7–12. doi: 10.1111/1753-6405.12158

Barton, J., Hine, R., and Pretty, J. (2009). The health benefits of walking in greenspaces of high natural and heritage value. *J. Integrat. Environ. Sci.* 6, 261–278. doi: 10.1080/19438150903378425

Barwais, F. A., Cuddihy, T. F., and Tomson, L. M. (2013). Physical activity, sedentary behavior and total wellness changes among sedentary adults: a 4-week randomized controlled trial. *Health Qual. Life Outcomes* 11:183. doi: 10.1186/1477-7525-11-183

Berg, T., Magala-Nyago, C., and Iversen, P. O. (2018). Nutritional status among adolescent girls in children's homes: anthropometry and dietary patterns. *Clin. Nutr.* 37, 926–933. doi: 10.1016/j.clnu.2017.03.020

Biagini, D., and Lazzaroni, C. (2018). Eutrophication risk arising from intensive dairy cattle rearing systems and assessment of the potential effect of mitigation strategies. *Agricul. Ecosyst. Environ.* 266, 76–83. doi: 10.1016/j.agee.2018.07.026

Bjørn, A., Kalbar, P., Nygaard, S. E., Kabins, S., Jensen, C. L., Birkved, M., et al. (2018). Pursuing necessary reductions in embedded GHG emissions of developed nations: will efficiency improvements and changes in consumption get us there? *Global Environ. Change* 52, 314–324. doi: 10.1016/j.gloenvcha.2018.08.001

Bodor, J. N., Rose, D., Farley, T. A., Swalm, C., and Scott, S. K. (2008). Neighbourhood fruit and vegetable availability and consumption: the role of small food stores in an urban environment. *Pub. Health Nutr.* 11, 413–420. doi: 10.1017/S1368980007000493

Boody, G., Vondracek, B., Andow, D. A., Krinke, M., Westra, J., Zimmerman, J., et al. (2005). Multifunctional agriculture in the United States. *BioScience* 55:27. doi: 10.1641/0006-3568(2005)055[0027:MAITUS]2.0.CO;2

Bravo-Ureta, B. E., Solís, D., Cocchi, H., and Quiroga, R. E. (2006). The impact of soil conservation and output diversification on farm income in Central American hillside farming. *Agricult. Econ.* 35, 267–276. doi: 10.1111/j.1574-0862.2006.00161.x

Browne, A. W., Harris, P. J. C., Hofny-Collins, A. H., Pasiecznik, N., and Wallace, R. R. (2000). Organic production and ethical trade: definition, practice and links. *Food Policy* 25, 69–89. doi: 10.1016/S0306-9192(99)00075-5

Burgess, C. P., Johnston, F. H., Bowman, D. M. J. S., and Whitehead, P. J. (2005). Healthy country: healthy people? Exploring the health benefits of indigenous natural resource management. *Aust. N. Z. J. Pub. Health* 29, 117–122. doi: 10.1111/j.1467-842X.2005.tb00060.x

Burlingame, B. (2012). "Sustainable diets and biodiversity - Directions and solutions for policy research and action," in *Proceedings of the International Scientific Symposium Biodiversity and Sustainable Diets United Against Hunger* (Rome: FAO).

Campbell, B. M., Vermeulen, S. J., Aggarwal, P. K., Corner-Dolloff, C., Girvetz, E., Loboguerrero, A. M., et al. (2016). Reducing risks to food security from climate change. *Global Food Secur.* 11, 34–43. doi: 10.1016/j.gfs.2016.06.002

Canals, L. M., Cowell, S., Sim, S., and Basson, L. (2007). Comparing domestic versus imported apples: a focus on energy use. *Environ. Sci. Pollut. Res.* 14, 338–344. doi: 10.1065/espr2007.04.412

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., and Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Issues Ecol.* 8:559–568. doi: 10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2

Carter, K. N., Kruse, K., Blakely, T., and Collings, S. (2011). The association of food security with psychological distress in New Zealand and any gender differences. *Soc. Sci. Med.* 72, 1463–1471. doi: 10.1016/j.socscimed.2011.03.009

Caspi, C. E., Sorensen, G., Subramanian, S. V., and Kawachi, I. (2012). The local food environment and diet: a systematic review. *Health Place* 18, 1172–1187. doi: 10.1016/j.healthplace.2012.05.006

Chaifetz, A., and Jagger, P. (2014). 40 Years of dialogue on food sovereignty: a review and a look ahead. *Global Food Secur.* 3, 85–91. doi: 10.1016/j.gfs.2014.04.002

Chodzko-Zajko, W. J., Proctor, D. N., Singh, M. A. F., Minson, C. T., Nigg, C. R., Salem, G. J., et al. (2009). Exercise and physical activity for older adults: medicine and science in sports and exercise. *Kinesiology* 41, 1510–1530. doi: 10.1249/MSS.0b013e3181a0c95c

Cleveland, D. A., Müller, N. M., Tranovich, A. C., Mazaroli, D. N., and Hinson, K. (2014). Local food hubs for alternative food systems: a case study from Santa Barbara County, California. *J. Rural Stud.* 35, 26–36. doi: 10.1016/j.jrurstud.2014.03.008

Cole, S. M., and Tembo, G. (2011). The effect of food insecurity on mental health: Panel evidence from rural Zambia. *Soc. Sci. Med.* 73, 1071–1079. doi: 10.1016/j.socscimed.2011.07.012

Cone, C. A., and Myhre, A. (2000). Community-supported agriculture: a sustainable alternative to industrial agriculture? (food and power: case studies in industrial agriculture and its alternatives in the United States) (statistical data included). *Human Org.* 59, 187–197. doi: 10.17730/humo.59.2.715203t206g2j153

Copena, D., and Simón, X. (2018). Wind farms and payments to landowners: opportunities for rural development for the case of Galicia. *Renew. Sustain. Energy Rev.* 95, 38–47. doi: 10.1016/j.rser.2018.06.043

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260. doi: 10.1038/387253a0

Dawson, J. (2013). Retailer activity in shaping food choice. *Food Qual. Prefere.* 28, 339–347. doi: 10.1016/j.foodqual.2012.09.012

Deckelbaum, R. J., Palm, C., Mutuo, P., and DeClerck, F. (2006). Econutrition: implementation models from the millennium villages project in Africa. *Food Nutri. Bull.* 27, 335–342. doi: 10.1177/156482650602700408

Deepika, V., and Vijayakumar, R. (2017). Impact of body mass index on arterial stiffness in young prehypertensives: a cross sectional study. *J. Res. Health Sci.* 18:e00402. Available online at: http://jrhs.umsha.ac.ir/index.php/JRHS/article/view/3565/

Dietary Guidelines Advisory Committee (2015). *Scientific Report of the 2015 Dietary Guidelines Advisory Committee: Advisory Report to the Secretary of Health and Human Services and the Secretary of Agriculture*. Washington, DC: U.S. Department of Agriculture, Agricultural Research Service. Available online at: https://health.gov/dietaryguidelines/2015-scientific-report/ (accessed June 14, 2019).

Dilkes-Hoffman, L. S., Lane, J. L., Grant, T., Pratt, S., Lant, P.A., and Laycock, B. (2018). Environmental impact of biodegradable food packaging when considering food waste. *J. Clean. Product.* 180, 325–334. doi: 10.1016/j.jclepro.2018.01.169

Dizon, F., and Herforth, A. (2018). *The Cost of Nutritious Food in South Asia*. Washington, DC: The World Bank.

Dodds, R. E., Tseëlon, E., and Weitkamp, E. L. C. (2008). Making sense of scientific claims in advertising. A study of scientifically aware consumers. *Pub. Understand. Sci.* 17, 211–230. doi: 10.1177/0963662506065559

Donini, L. M., Dernini, S., Lairon, D., Serra-Majem, L., Amiot, M. J., Del Balzo, V., et al. (2016). A consensus proposal for nutritional indicators to assess the sustainability of a healthy diet: the mediterranean diet as a case study. *Front. Nutr.* 3:37. doi: 10.3389/fnut.2016.00037

Downs, S. M., Payne, A., and Fanzo, J. (2017). The development and application of a sustainable diets framework for policy analysis: a case study of Nepal. *Food Policy* 70, 40–49. doi: 10.1016/j.foodpol.2017.05.005

D'Sylva, A., and Beagan, B. (2011). 'Food is culture, but it's also power': the role of food in ethnic and gender identity construction among Goan Canadian women. *J. Gender Stud.* 20, 279–289. doi: 10.1080/09589236.2011.593326

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z –I., Knowler, D. J., Lévêque, C., et al. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biol. Rev.* 81, 163–182. doi: 10.1017/S1464793105006950

Duffey, K. J., Gordon-Larsen, P., Shikany, J. M., Guilkey, D., Jacobs, D. R., and Popkin, B. M. (2010). Food price and diet and health outcomes: 20 years of the CARDIA study. *Arch. Intern. Med.* 170, 420–426. doi: 10.1001/archinternmed.2009.545

Dupraz, C. L., and Postolle, A. (2013). Food sovereignty and agricultural trade policy commitments: how much leeway do West African nations have? *Food Policy* 38, 115–125. doi: 10.1016/j.foodpol.2012.11.005

Dupuis, E. M., and Goodman, D. (2005). Should we go 'home' to eat?: toward a reflexive politics of localism. (Report). *J. Rural Stud.* 21, 359–371. doi: 10.1016/j.jrurstud.2005.05.011

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Kadner, S., Minx, J. C., Brunner, S., et al. (2014). *Climate Change 2014: Mitigation of Climate Change Technical Summary*. Available online at: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_technical-summary.pdf (accessed June 13, 2019).

Edge, M. K., and Barnett, J. L. (2009). Development of animal welfare standards for the livestock transport industry: process, challenges, and implementation. *J. Vet. Behav. Clin. Appl. Res.* 4, 187–192. doi: 10.1016/j.jveb.2009.07.001

Edwards, J., Burn, S., Crossin, E., and Othman, M. (2018). Life cycle costing of municipal food waste management systems: the effect of environmental externalities and transfer costs using local government case studies. *Resour. Conserv. Recycl.* 138, 118–129. doi: 10.1016/j.resconrec.2018.06.018

Edwards, M. K., and Loprinzi, P. D. (2017). Experimentally increasing sedentary behavior results in decreased life satisfaction. *Health Promot. Perspect* 7, 88–94. doi: 10.15171/hpp.2017.16

Edwards-Jones, G. (2010). Does eating local food reduce the environmental impact of food production and enhance consumer health? *Proc. Nutri. Soc.* 69, 582–591. doi: 10.1017/S0029665110002004

Ellison, B., Lusk, J. L., and Davis, D. (2014). The impact of restaurant calorie labels on food choice: results from a field experiment. *Econ. Inquiry* 52, 666–681. doi: 10.1111/ecin.12069

Eory, V., Pellerin, S., Garcia, G. C., Lehtonen, H., Licite, I., Mattila, H., et al. (2018). Marginal abatement cost curves for agricultural climate policy: state-of-the art, lessons learnt and future potential. *J. Clean. Product.* 182, 705–716. doi: 10.1016/j.jclepro.2018.01.252

Eshel, G., Shepon, A., Makov, T., and Milo, R. (2014). Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *Proc. Natl. Acad. Sci.U.S.A.* 111, 11996–12001. doi: 10.1073/pnas.1402183111

Esteve-Llorens, X., Darriba, C., Moreira, M. T., Feijoo, G., and González-García, S. (2019). Towards an environmentally sustainable and healthy Atlantic dietary pattern: life cycle carbon footprint and nutritional quality. *Sci. Total Environ.* 646, 704–715. doi: 10.1016/j.scitotenv.2018.07.264

Ewert, F., Rounsevell, M. D. A., Reginster, I., Metzger, M. J., and Leemans, R. (2005). Future scenarios of European agricultural land use. *Agricult. Ecosyst. Environ.* 107, 101–116. doi: 10.1016/j.agee.2004.12.003

Eyles, H., Ni Mhurchu, C., Nghiem, N., and Blakely, T. (2012). Food pricing strategies, population diets, and non-communicable disease: a systematic review of simulation studies. *PLoS Med* 9:e1001353. doi: 10.1371/journal.pmed.1001353

Fanzo, J. C., Downs, S., Marshall, Q. E., de Pee, S., and Bloem, M. W. (2017). "Value chain focus on food and nutrition security," in *Nutrition and Health in a Developing World,* eds S. de Pee, D. Taren, and M. W. Bloem (New York, NY: Springer International Publishing), 753–770.

Ferrer-Martí, L., Ferrer, I., Sánchez, E., and Garfí, M. (2018). A multi-criteria decision support tool for the assessment of household biogas digester programmes in rural areas. A case study in Peru. *Renew. Sustain. Energy Rev.* 95, 74–83. doi: 10.1016/j.rser.2018.06.064

Fischer, C. G., and Garnett, T. (2016). *Food and Agriculture Organization of the United Nations, University of Oxford and Food Climate Research Network. Plates, Pyramids, and Planets: Developments in National Healthy and Sustainable Dietary Guidelines: A State of Play Assessment* (Oxford).

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., et al. (2011). Solutions for a cultivated planet. *Nature* 478, 337–342. doi: 10.1038/nature10452

Food and Agriculture Organization (2002). *Safe Food and Nutritious Diet for the Consumer*. Available online at: http://www.fao.org/worldfoodsummit/sideevents/papers/y6656e.htm (accessed July 29, 2019).

Food and Agriculture Organization (2009). *How to Feed the World in 2050*. Available online at: http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf (accessed June 14, 2019).

Forssell, S., and Lankoski, L. (2015). The sustainability promise of alternative food networks: an examination through "alternative" characteristics. *Agricult. Human Values* 32, 63–75. doi: 10.1007/s10460-014-9516-4

Fresco, L. O. (2009). Challenges for food system adaptation today and tomorrow. *Environ. Sci. Policy* 12, 378–385. doi: 10.1016/j.envsci.2008.11.001

Friedmann, H. (2007). Scaling up: bringing public institutions and food service corporations into the project for a local, sustainable food system in Ontario. *Agricult. Human Values* 24, 389–398. doi: 10.1007/s10460-006-9040-2

Frison, E. A., Smith, I. F., Johns, T., Cherfas, J., and Eyzaguirre, P. B. (2006). Agricultural biodiversity, nutrition, and health: making a difference to hunger and nutrition in the developing world. *Food Nutr. Bull.* 27, 167–179. doi: 10.1177/156482650602700208

Fu, H.-Z., Fang, K., and Fang, C.-L. (2018). Characteristics of scientific impact of resources conservation and recycling in the past 30 years. *Resour. Conserv. Recycl.* 137, 251–259. doi: 10.1016/j.resconrec.2018.06.021

Galhena, D. H., Freed, R., and Maredia, K. M. (2013). Home gardens: a promising approach to enhance household food security and wellbeing. *Agricult. Food Secur.* 2:7. doi: 10.1186/2048-7010-2-8

Garnett (2014). *What is a Sustainable Diet?* Available online at: https://www.fcrn.org.uk/sites/default/files/fcrn_what_is_a_sustainable_healthy_diet_final.pdf (accessed June 13, 2019).

Garnett, T. (2011). Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy* 36, S23–S32. doi: 10.1016/j.foodpol.2010.10.010

Gittelsohn, J., Rowan, M., and Gadhoke, P. (2012). Interventions in small food stores to change the food environment, improve diet, and reduce risk of chronic disease. *Prev. Chronic. Dis.* 9:E59. doi: 10.5888/pcd9.110015

Global Panel (2017). *Global Panel at the Global Nutrition Summit 2017. Global Panel*. Available online at: https://www.glopan.org/news/global-panel-at-the-global-nutrition-summit-2017/ (accessed June 14, 2019).

Gomiero, T., Pimentel, D., and Paoletti, M. G. (2011). Is there a need for a more sustainable agriculture? *Critical Rev. Plant Sci.* 30, 6–23. doi: 10.1080/07352689.2011.553515

González-García, S., Esteve-Llorens, X., Moreira, M. T., and Feijoo, G. (2018). Carbon footprint and nutritional quality of different human dietary choices. *Sci. Total Environ.* 644, 77–94. doi: 10.1016/j.scitotenv.2018.06.339

Govindan, K. (2018). Sustainable consumption and production in the food supply chain: a conceptual framework. *Int. J. Product. Econ.* 195, 419–431. doi: 10.1016/j.ijpe.2017.03.003

Graham, R. D., Welch, R. M., and Bouis, H. E. (2001). Addressing micronutrient malnutrition through enhancing the nutritional quality of staple foods: principles, perspectives and knowledge gaps. *Adv. Agron.* 70, 77–142. doi: 10.1016/S0065-2113(01)70004-1

Grunert, K. G. (2005). Food quality and safety: consumer perception and demand. *Euro. Rev. Agricult. Econ.* 32, 369–391. doi: 10.1093/eurrag/jbi011

Grunert, K. G., Hieke, S., and Wills, J. (2014). Sustainability labels on food products: Consumer motivation, understanding and use. *Food Policy* 44, 177–189. doi: 10.1016/j.foodpol.2013.12.001

Gussow, J. D., and Clancy, K. L. (1986). Dietary guidelines for sustainability. *J. Nutri. Edu*. 18, 1–5. doi: 10.1016/S0022-3182(86)80255-2

Hallström, E., Davis, J., Woodhouse, A., and Sonesson, U. (2018). Using dietary quality scores to assess sustainability of food products and human diets: a systematic review. *Ecol. Indicat.* 93, 219–230. doi: 10.1016/j.ecolind.2018.04.071

Hanes, R. J., Gopalakrishnan, V., and Bakshi, B. R. (2018). Including nature in the food-energy-water nexus can improve sustainability across multiple ecosystem services. *Res. Conserv. Recycl.* 137, 214–228. doi: 10.1016/j.resconrec.2018.06.003

Havstad, K. M., Peters, D. P.C., Skaggs, R., Brown, C., Bestelmeyer, B., Fredrickson, E., et al. (2007). Ecological services to and from rangelands of the United States. *Ecol. Econ.* 64, 261–268. doi: 10.1016/j.ecolecon.2007.08.005

He, P., Baiocchi, G., Hubacek, K., Feng, K., and Yu, Y. (2018). The environmental impacts of rapidly changing diets and their nutritional quality in China. *Nat. Sustain.* 1, 122–127. doi: 10.1038/s41893-018-0035-y

Hendrickson, M. K., James, H. S., Kendall, A., and Sanders, C. (2018). The assessment of fairness in agricultural markets. *Geoforum* 96, 41–50. doi: 10.1016/j.geoforum.2018.07.020

Herforth, A., and Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Sec*. 7, 505–520. doi: 10.1007/s12571-015-0455-8

Herforth, A., Ahmed, S., DeClerck, F., Fanzo, J., and Remans, R. (2017). *UNSCN-News42-2017.pdf*. Available online at: https://www.unscn.org/uploads/web/news/UNSCN-News42-2017.pdf (accessed June 14, 2019).

Hersch, D., Perdue, L., Ambroz, T., and Boucher, J. L. (2014). The impact of cooking classes on food-related preferences, attitudes, and behaviors of school-aged children: a systematic review of the evidence, 2003–2014. *Prevent. Chronic Dis.* 11:E193. doi: 10.5888/pcd11.140267

High Level Panel (2017). *Report of the High Level Panel on the Assessment of Key Legislation and the Acceleration of Fundamental Change*. Available online at: https://www.parliament.gov.za/storage/app/media/Pages/2017/october/High_Level_Panel/HLP_Report/HLP_report.pdf (accessed June 14, 2019).

Hinrichs, C. (2000). Embeddedness and local food systems: notes on two types of direct agricultural market. *J. Rural Studies* 16, 295–303. doi: 10.1016/S0743-0167(99)00063-7

Hoelzer, K., Moreno Switt, A. I., Wiedmann, M., and Boor, K. J. (2018). Emerging needs and opportunities in foodborne disease detection and prevention: from tools to people. *Food Microbiol.* 75, 65–71. doi: 10.1016/j.fm.2017.07.006

Horrigan, L., Lawrence, R. S., and Walker, P. (2002). How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environ. Health Perspect.* 110, 445–456. doi: 10.1289/ehp.02110445

Hu, Y., Huang, Y., Tang, J., Gao, B., Yang, M., Meng, F., et al. (2018). Evaluating agricultural grey water footprint with modeled nitrogen emission data. *Res. Conserv. Recycl.* 138, 64–73. doi: 10.1016/j.resconrec.2018.04.020

Hunter, D., Foster, M., McArthur, J.O., Ojha, R., Petocz, P., and Samman, S. (2011). Evaluation of the micronutrient composition of plant foods produced by organic and conventional agricultural methods. *Crit. Rev. Food Sci. Nutr.* 51, 571–582. doi: 10.1080/10408391003721701

Hyland, R., Stacy, R., Adamson, A., and Moynihan, P. (2006). Nutrition-related health promotion through an after-school project: the responses of children and their families. *Soc. Sci. Med.* 62, 758–768. doi: 10.1016/j.socscimed.2005.06.032

Ibarra, R., Rich, K. M., Adasme, M., Kamp, A., Singer, R. S., Atlagich, M., et al. (2018). Animal production, animal health and food safety:

gaps and challenges in the chilean industry. *Food Microbiol.* 75, 114–118. doi: 10.1016/j.fm.2017.10.004
Intergovernmental Panel in Climate Change (2013). *AR5 Climate Change 2013: The Physical Science Basis*. Geneva: IPCC.
Intergovernmental Panel on Climate Changes (2014). *AR5 Climate Change 2014: Mitigation of Climate Change*. Geneva: IPCC.
Jenkins, D. J., Sievenpiper, J. L., Pauly, D., Sumaila, U. R., Kendall, C. W., and Mowat, F. M. (2009). Are dietary recommendations for the use of fish oils sustainable? *CMAJ* 180, 633–637. doi: 10.1503/cmaj.081274
Jessiman-Perreault, G., and McIntyre, L. (2017). The household food insecurity gradient and potential reductions in adverse population mental health outcomes in Canadian adults. *SSM Populat. Health* 3, 464–472. doi: 10.1016/j.ssmph.2017.05.013
John Hopkins Center (2016). *John Hopkins Center for a Livable Future*. The Emergence of the Food Voter. Available online at: https://www.jhsph.edu/research/centers-and-institutes/johns-hopkins-center-for-a-livable-future/_pdf/briefs/data/food-voter.pdf (accessed June 13, 2019).
Johns, T., Powell, B., Maundu, P., and Eyzaguirre, P. B. (2013). Agricultural biodiversity as a link between traditional food systems and contemporary development, social integrity and ecological health. *J. Sci. Food Agricult*. 93, 3433–3442. doi: 10.1002/jsfa.6351
Johnson-Down, L., and Egeland, G. M. (2010). Adequate nutrient intakes are associated with traditional food consumption in nunavut inuit children aged 3-5 years. *J. Nutr*. 140, 1311–1316. doi: 10.3945/jn.109.117887
Johnston, J. L., Fanzo, J. C., and Cogill, B. (2014). Understanding sustainable diets: a descriptive analysis of the determinants and processes that influence diets and their impact on health, food security, and environmental sustainability123. *Adv. Nutr.* 5, 418–429. doi: 10.3945/an.113.005553
Jones, A.D., Hoey, L., Blesh, J., Miller, L., Green, A., and Shapiro, L.F. (2016). A systematic review of the measurement of sustainable diets. *Adv. Nutr.* 7, 641–664. doi: 10.3945/an.115.011015
Juul, F., Martinez-Steele, E., Parekh, N., Monteiro, C. A., and Chang, V. W. (2018). Ultra-processed food consumption and excess weight among US adults. *Br. J. Nutr*. 120, 90–100. doi: 10.1017/S0007114518001046
Kahleova, H., Levin, S., and Barnard, N. D. (2018). Vegetarian dietary patterns and cardiovascular disease. *Prog. Cardiovasc. Dis.* 61, 54–61. doi: 10.1016/j.pcad.2018.05.002
Kalbar, P. P., Birkved, M., Hauschild, M., Kabins, S., and Nygaard, S. E. (2018). Environmental impact of urban consumption patterns: drivers and focus points. *Res. Conserv. Recycl.* 137, 260–269. doi: 10.1016/j.resconrec.2018.06.019
Kalof, L., Dietz, T., Stern, P. C., and Guagnano, G. A. (1999). Social psychological and structural influences on vegetarian beliefs. *Rural. Sociol.* 64, 500–511. doi: 10.1111/j.1549-0831.1999.tb00364.x
Kamat, P. V. (2007). Meeting the clean energy demand: nanostructure architectures for solar energy conversion. *J. Phys. Chem. C* 111, 2834–2860. doi: 10.1021/jp066952u
Kant, A. K., Schatzkin, A., Harris, T. B., Ziegler, R. G., and Block, G. (1993). Dietary diversity and subsequent mortality in the first national health and nutrition examination survey epidemiologic follow-up study. *Am. J. Clin. Nutr*. 57, 434–440. doi: 10.1093/ajcn/57.3.434
Kataoka, A. I., Enache, E., Black, D. G., Elliott, P. H., Napier, C. D., Podolak, R., et al. (2014). Survival of Salmonella Tennessee, Salmonella Typhimurium DT104, and Enterococcus faecium in peanut paste formulations at two different levels of water activity and fat. *J. Food Prot*. 77, 1252–1259. doi: 10.4315/0362-028X.JFP-13-553
Keflie, T. S., Samuel, A., Lambert, C., Nohr, D., and Biesalski, H. K. (2018). Dietary patterns and risk of micronutrient deficiencies: their implication for nutritional intervention in Ethiopia. *Jnhfs* 6, 1–16. doi: 10.15226/jnhfs.2018.001120
Kemps, E., Tiggemann, M., and Hollitt, S. (2014). Exposure to television food advertising primes food-related cognitions and triggers motivation to eat. *Psychol. Health* 29, 1–27. doi: 10.1080/08870446.2014.918267
Khan, A., and Tandon, P. (2017). "Closing the Loop: 'Systems perspective' for the design of food packaging to facilitate material recovery,". in *Research into Design for Communities, Volume 2*, eds A. Chakrabarti, and D. Chakrabarti (Singapore: Springer), 349–359. doi: 10.1007/978-981-10-3521-0_30
King, C. A. (2008). Community resilience and contemporary agri-ecological systems: reconnecting people and food, and people with people. *Syst. Res. Behav. Sci.* 25, 111–124. doi: 10.1002/sres.854
Kremer, P., and Deliberty, T. L. (2011). Local food practices and growing potential: Mapping the case of Philadelphia. *Appl. Geography* 31, 1252–1261. doi: 10.1016/j.apgeog.2011.01.007
Kuo, J.-C., and Chen, M.-C. (2010). Developing an advanced multi-temperature joint distribution system for the food cold chain. *Food Control* 21, 559–566. doi: 10.1016/j.foodcont.2009.08.007
Kwon, Y.-I., Apostolidis, E., Kim, Y.-C., and Shetty, K. (2007). Health benefits of traditional corn, beans, and pumpkin: *in vitro* studies for hyperglycemia and hypertension management. *J. Med. Food* 10, 266–275. doi: 10.1089/jmf.2006.234
Lado, B. H., and Yousef, A. E. (2002). Alternative food-preservation technologies: efficacy and mechanisms. *Microbes Infect.* 4, 433–440. doi: 10.1016/S1286-4579(02)01557-5
Lal, R. (2018). Sustainable intensification of China's agroecosystems by conservation agriculture. *Int. Soil Water Conserv. Res.* 6, 1–12. doi: 10.1016/j.iswcr.2017.11.001
Lalani, B., Dorward, P., Holloway, G., and Wauters, E. (2016). Smallholder farmers' motivations for using conservation agriculture and the roles of yield, labour and soil fertility in decision making. *Agricult. Syst.* 146, 80–90. doi: 10.1016/j.agsy.2016.04.002
Larrick, J. W., and Mendelsohn, A. R. (2018). Finally a regimen to extend human life expectancy. *Rejuvenation Res.* 21, 278–282. doi: 10.1089/rej.2018.2088
Larson, N. I., Perry, C. L., Story, M., and Neumark-Sztainer, D. (2006). Food preparation by young adults is associated with better diet quality. *J. Am. Dietetic Assoc.* 106, 2001–2007. doi: 10.1016/j.jada.2006.09.008
Lazzarini, G. A., Visschers, V. H. M., and Siegrist, M. (2018). How to improve consumers' environmental sustainability judgements of foods. *J. Clean. Product*. 198, 564–574. doi: 10.1016/j.jclepro.2018.07.033
Lee, M.-J., Popkin, B. M., and Kim, S. (2002). The unique aspects of the nutrition transition in South Korea: the retention of healthful elements in their traditional diet. *Public Health Nutr.* 5, 197–203. doi: 10.1079/PHN2001294
Lee, M. H., Lee, H. J., and Ryu, P. D. (2001). Public health risks: chemical and antibiotic residues - review -. *AAJA. Sci.* 14, 402–413. doi: 10.5713/ajas.2001.402
Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., and Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525, 367–371. doi: 10.1038/nature15371
Lentz, G., Connelly, S., Mirosa, M., and Jowett, T. (2018). Gauging attitudes and behaviours: Meat consumption and potential reduction. *Appetite* 127, 230–241. doi: 10.1016/j.appet.2018.04.015
Leon, A., and Ishihara, K. N. (2018). Influence of allocation methods on the LC-CO2 emission of an agrivoltaic system. *Resour. Conserv. Recycl.* 138, 110–117. doi: 10.1016/j.resconrec.2018.06.017
Leventon, J., and Laudan, J. (2017). Local food sovereignty for global food security? highlighting interplay challenges. *Geoforum* 85, 23–26. doi: 10.1016/j.geoforum.2017.07.002
Levidow, L., and Psarikidou, K. (2011). Food relocalization for environmental sustainability in Cumbria. *Sustainability* 3, 692–719. doi: 10.3390/su3040692
Li, X., Campana, P. E., Li, H., Yan, J., and Zhu, K. (2017). Energy storage systems for refrigerated warehouses. *Energy Procedia* 143, 94–99. doi: 10.1016/j.egypro.2017.12.653
Lin, A. Y.-C., Huang, S. T.-Y., and Wahlqvist, M. L. (2009). Waste management to improve food safety and security for health advancement. *Asia Pac. J. Clin. Nutr.* 18, 538–545.
Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., et al. (2014). Climate-smart agriculture for food security. *Nat. Clim. Change* 4, 1068–1072. doi: 10.1038/nclimate2437
López-González, A., Domenech, B., and Ferrer-Martí, L. (2018). Formative evaluation of sustainability in rural electrification programs from a management perspective: a case study from Venezuela. *Renew. Sustain. Energy Rev.* 95, 95–109. doi: 10.1016/j.rser.2018.07.024
Lowe, M. R., and Butryn, M. L. (2007). Hedonic hunger: a new dimension of appetite? *Physiol. Behav*. 91, 432–439. doi: 10.1016/j.physbeh.2007.04.006
Macdiarmid, J. I. (2014). Seasonality and dietary requirements: will eating seasonal food contribute to health and environmental sustainability? *Proc. Nutr. Soc.* 73, 368–375. doi: 10.1017/S0029665113003753

Macrae, R., Szabo, M., Anderson, K., Louden, F., and Trillo, S. (2012). Empowering the citizen-consumer: re-regulating consumer information to Support the Transition to sustainable and health promoting food systems in Canada. *Sustainability* 4, 2146–2175. doi: 10.3390/su4092146

Magni, P., Bier, D. M., Pecorelli, S., Agostoni, C., Astrup, A., Brighenti, F., et al. (2017). Perspective: improving nutritional guidelines for sustainable health policies: current status and perspectives. *Adv. Nutri.* 8, 532–545. doi: 10.3945/an.116.014738

Magnus, A., Haby, M. M., Carter, R., and Swinburn, B. (2009). The cost-effectiveness of removing television advertising of high-fat and/or high-sugar food and beverages to Australian children. *Int. J. Obesity* 33, 1094–1102. doi: 10.1038/ijo.2009.156

Maloni, M., and Brown, M. (2006). Corporate social responsibility in the supply Chain: an application in the food industry. *J. Business Ethics* 68, 35–52. doi: 10.1007/s10551-006-9038-0

Mancini, P., Marchini, A., and Simeone, M. (2017). Which are the sustainable attributes affecting the real consumption behaviour? Consumer understanding and choices. *Br. Food J.* 119, 1839–1853. doi: 10.1108/BFJ-11-2016-0574

Martin, M. S., Maddocks, E., Chen, Y., Gilman, S. E., and Colman, I. (2016). Food insecurity and mental illness: disproportionate impacts in the context of perceived stress and social isolation. *Public Health* 132, 86–91. doi: 10.1016/j.puhe.2015.11.014

Mason, P., and Lang, T. (2017). *Sustainable Diets: How Ecological Nutrition Can Transform Consumption and the Food System*. London: Routledge.

Medact and Eating Better Alliance Policy Briefing (2017). *A Healthy and Sustainable Food Future*. Available online at: https://www.medact.org/wp-content/uploads/2017/03/A-Healthy-Sustainable-Food-Future.pdf (accessed June 13, 2019).

Melzer, K., Schutz, Y., Boulvain, M., and Kayser, B. (2010). Physical activity and pregnancy: cardiovascular adaptations, recommendations and pregnancy outcomes. *Sports Med.* 40, 493–507. doi: 10.2165/11532290-000000000-00000

Meneghetti, A., Rold, G. D., and Cortella, G. (2018). Sustainable refrigerated food transport: searching energy efficient routes. *IFAC PapersOnLine* 51, 618–623. doi: 10.1016/j.ifacol.2018.08.387

Miller, B. D. D., and Welch, R. M. (2013). Food system strategies for preventing micronutrient malnutrition. *Food Policy* 42, 115–128. doi: 10.1016/j.foodpol.2013.06.008

Milner, J., and Green, R. (2018). Sustainable diets are context specific but are they realistic? *Lancet Planet. Health* 2, e425–e426. doi: 10.1016/S2542-5196(18)30207-9

Mirmiran, P., Azadbakht, L., Esmaillzadeh, A., and Azizi, F. (2004). Dietary diversity score in adolescents–a good indicator of the nutritional adequacy of diets: Tehran lipid and glucose study. *Asia Pac. J. Clin. Nutr.* 13, 56–60. Available online at: http://apjcn.nhri.org.tw/server/APJCN/13/1/56.pdf

Misra, A., Sharma, R., Gulati, S., Joshi, S. R., Sharma, V., Ibrahim, A., et al. (2011). Consensus dietary guidelines for healthy living and prevention of obesity, the metabolic syndrome, diabetes, and related disorders in Asian Indians. *Diabetes Technol. Ther*. 13, 683–694. doi: 10.1089/dia.2010.0198

Moffatt, C. R. M., Howard, P. J., and Burns, T. (2011). A mild outbreak of gastroenteritis in long-term care facility residents due to Clostridium perfringens, Australia 2009. *Foodborne Pathog. Dis*. 8, 791–796. doi: 10.1089/fpd.2010.0785

Monteiro, C. A., Cannon, G., Moubarac, J. C., Martins, A. P. B., Martins, C. A., Garzillo, J., et al. (2015). Dietary guidelines to nourish humanity and the planet in the twenty-first century. A blueprint from Brazil. *Public Health Nutr.* 18, 2311–2322. doi: 10.1017/S1368980015002165

Monteiro, C. A., Levy, R. B., Claro, R. M., de Castro, I. R. R., and Cannon, G. (2011). Increasing consumption of ultra-processed foods and likely impact on human health: evidence from Brazil. *Public Health Nutr.* 14, 5–13. doi: 10.1017/S1368980010003241

Mook, A., and Overdevest, C. (2018). Does fairtrade certification meet producers' expectations related to participating in mainstream markets? an analysis of advertised benefits and perceived impact. *Sustain. Develop.* 26, 269–280. doi: 10.1002/sd.1700

Myers, S. S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A. D., Bloom, A. J., et al. (2014). Increasing CO2 threatens human nutrition. *Nature* 510, 139–142. doi: 10.1038/nature13179

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D., et al. (2009). Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front. Ecol. Environ.* 7, 4–11. doi: 10.1890/080023

Nelson, M.E., Hamm, M.W., Hu, F.B., Abrams, S., and Griffin, T.S. (2016). Alignment of healthy dietary patterns and environmental sustainability: a systematic review. *Adv. Nutri.* 7, 1005–1025. doi: 10.3945/an.116.012567

New, S. J. (2015). Modern slavery and the supply chain: the limits of corporate social responsibility? *Supply Chain Manage.* 20, 697–707. doi: 10.1108/SCM-06-2015-0201

Nost, E. (2014). Scaling-up local foods: commodity practice in community supported agriculture (CSA). *J. Rural Studies* 34, 152–160. doi: 10.1016/j.jrurstud.2014.01.001

O'Neill, K. J. (2014). Situating the 'alternative' within the 'conventional' – local food experiences from the East Riding of Yorkshire, UK. *J. Rural Stud.* 35, 112–122. doi: 10.1016/j.jrurstud.2014.04.008

Onyango, A. W. (2003). Dietary diversity, child nutrition and health in contemporary African communities. *Comp. Biochem. Physiol. Part A Mol. Integr. Physiol.* 136, 61–69. doi: 10.1016/S1095-6433(03)00071-0

Oya, C., Schaefer, F., and Skalidou, D. (2018). The effectiveness of agricultural certification in developing countries: a systematic review. *World Develop.* 112, 282–312. doi: 10.1016/j.worlddev.2018.08.001

Pan, X.-R., Li, G. W., Hu, Y. H., Wang, J. X., Yang, W. Y., An, Z. X. et al. (1997). Effects of diet and exercise in preventing NIDDM in people with impaired glucose tolerance: the Da Qing IGT and diabetes study. *Diabetes Care* 20, 537–544. doi: 10.2337/diacare.20.4.537

Pimentel, D., and Pimentel, M. (2003). Sustainability of meat-based and plant-based diets and the environment. *Am. J. Clin. Nutr.* 78, 660S−663S. doi: 10.1093/ajcn/78.3.660S

Popkin, B. M., and Reardon, T. (2018). Obesity and the food system transformation in Latin America. *Obes. Rev.* 19, 1028–1064. doi: 10.1111/obr.12694

Poppe, K. J., Wolfert, S., Verdouw, C., and Verwaart, T. (2013). Information and communication technology as a driver for change in agri-food chains, La technologie de l'information et de la communication comme moteur du changement dans les filières agroalimentaires, Informations- und Kommunikationstechnik als Triebfeder für Veränderung in den Wertschöpfungsketten der Agrar- und Ernährungswirtschaft. *EuroChoices* 12, 60–65. doi: 10.1111/1746-692X.12022

Poti, J. M., Braga, B., and Qin, B. (2017). Ultra-processed food intake and obesity: what really matters for health-processing or nutrient content? *Curr. Obes. Rep.* 6, 420–431. doi: 10.1007/s13679-017-0285-4

Price, J. C., and Leviston, Z. (2014). Predicting pro-environmental agricultural practices: the social, psychological and contextual influences on land management. *J. Rural Studies* 34, 65–78. doi: 10.1016/j.jrurstud.2013.10.001

Profeta, A., and Hamm, U. (2019). Do consumers prefer local animal products produced with local feed? results from a discrete-choice experiment. *Food Qual Prefere.* 71, 217–227. doi: 10.1016/j.foodqual.2018.07.007

Raymond, C. M., Bryan, B. A., MacDonald, D. H., Cast, A., Strathearn, S., Grandgirard, A., et al. (2009). Mapping community values for natural capital and ecosystem services. *Ecol. Econ.* 68, 1301–1315. doi: 10.1016/j.ecolecon.2008.12.006

Remans, R., Wood, S. A., Saha, N., Anderman, T. L., and DeFries, R. S. (2014). Measuring nutritional diversity of national food supplies. *Global Food Security* 3, 174–182. doi: 10.1016/j.gfs.2014.07.001

Renzaho, A. M. N., Swinburn, B., and Burns, C. (2008). Maintenance of traditional cultural orientation is associated with lower rates of obesity and sedentary behaviours among African migrant children to Australia. *Int. J. Obesity* 32, 594–600. doi: 10.1038/ijo.2008.2

Rich, K. M., Dizyee, K., Nguyen, T. H., Duong, N. H., Pham, V. H., Nguyen, T. N., et al. (2018). Quantitative value chain approaches for animal health and food safety. *Food Microbiol.* 75, 103–113. doi: 10.1016/j.fm.2017.09.018

Rich, K. M., Ross, R. B., Baker, A. D., and Negassa, A. (2011). Quantifying value chain analysis in the context of livestock systems in developing countries. *Food Policy* 36, 214–222. doi: 10.1016/j.foodpol.2010.11.018

Rivera, D., Toledo, V., Reyes-Jara, A., Navarrete, P., Tamplin, M., Kimura, B., et al. (2018). Approaches to empower the implementation of new tools to detect and prevent foodborne pathogens in food processing. *Food Microbiol.* 75, 126–132. doi: 10.1016/j.fm.2017.07.009

Romani, S., Grappi, S., Bagozzi, R. P., and Barone, A. M. (2018). Domestic food practices: a study of food management behaviors and the role of food preparation planning in reducing waste. *Appetite* 121, 215–227. doi: 10.1016/j.appet.2017.11.093

Rose, D., and Richards, R. (2004). Food store access and household fruit and vegetable use among participants in the US Food Stamp Program. *Public Health Nutr.* 7, 1081–1088. doi: 10.1079/PHN2004648

Ruini, L.F., Ciati, R., Pratesi, C.A., Marino, M., Principato, L., and Vannuzzi, E. (2015). Working toward healthy and sustainable diets: the "double pyramid model" developed by the Barilla center for food and nutrition to raise awareness about the environmental and nutritional impact of foods. *Front. Nutr.* 2:9. doi: 10.3389/fnut.2015.00009

Sabbahi, M., Li, J., Davis, C., and Downs, S. M. (2018). "Chapter nine - the role of the sustainable development goals to reduce the global burden of malnutrition," in *Advances in Food Security and Sustainability,* eds D. Barling, and J. Fanzo (Cambridge: Elsevier), 277–333. doi: 10.1016/bs.af2s.2018.09.007

Salas-Salvadó, J., Becerra-Tomás, N., García-Gavilán, J. F., Bulló, M., and Barrubés, L. (2018). Mediterranean diet and cardiovascular disease prevention: what do we know? *Prog. Cardiovasc. Dis.* 61, 62–67. doi: 10.1016/j.pcad.2018.04.006

Sánchez-Safont, E. L., Aldureid, A., Lagarón, J. M., Gámez-Pérez, J., and Cabedo, L. (2018). Biocomposites of different lignocellulosic wastes for sustainable food packaging applications. *Composites Part B* 145, 215–225. doi: 10.1016/j.compositesb.2018.03.037

Sarkar, S. F., Poon, J. S., Lepage, E., Bilecki, L., and Girard, B. (2017). Enabling a sustainable and prosperous future through science and innovation in the bioeconomy at agriculture and agri-food Canada. *N. Biotechnol.* 40, 70–75. doi: 10.1016/j.nbt.2017.04.001

Satija, A., and Hu, F. B. (2018). Plant-based diets and cardiovascular health. *Trends Cardiovasc. Med.* 28, 437–441. doi: 10.1016/j.tcm.2018.02.004

Sbicca, J. (2015). Food labor, economic inequality, and the imperfect politics of process in the alternative food movement. *Agricult. Human Values* 32, 675–687. doi: 10.1007/s10460-015-9582-2

Schanes, K., Dobernig, K., and Gözet, B. (2018). Food waste matters - a systematic review of household food waste practices and their policy implications. *J. Clean. Product.* 182, 978–991. doi: 10.1016/j.jclepro.2018.02.030

Schmidt, K., and Matthies, E. (2018). Where to start fighting the food waste problem? Identifying most promising entry points for intervention programs to reduce household food waste and overconsumption of food. *Res. Conserv. Recycl.* 139, 1–14. doi: 10.1016/j.resconrec.2018.07.023

Schnabel, L., Buscail, C., Sabate, J. M., Bouchoucha, M., Kesse-Guyot, E., Allès, B., et al. (2018). Association between ultra-processed food consumption and functional gastrointestinal disorders: results from the french nutrinet-santé cohort. *Am. J. Gastroenterol.* 113, 1217–1228. doi: 10.1038/s41395-018-0137-1

Seed, B. (2015). Sustainability in the Qatar national dietary guidelines, among the first to incorporate sustainability principles. *Public Health Nutr.* 18, 2303–2310. doi: 10.1017/S1368980014002110

Shinn, J. E. (2016). Adaptive environmental governance of changing social-ecological systems: empirical insights from the Okavango Delta, Botswana. *Global Environ. Change* 40, 50–59. doi: 10.1016/j.gloenvcha.2016.06.011

Shreck, A., Getz, C., and Feenstra, G. (2006). Social sustainability, farm labor, and organic agriculture: findings from an exploratory analysis. *Agricult. Human Values* 23, 439–449. doi: 10.1007/s10460-006-9016-2

Siegel, K. R., Ali, M. K., Srinivasiah, A., Nugent, R. A., and Narayan, K. M. V. (2014). Do we produce enough fruits and vegetables to meet global health need? *PLoS ONE* 9:e0104059. doi: 10.1371/journal.pone.0104059

Singh, A., Kumari, S., Malekpoor, H., and Mishra, N. (2018). Big data cloud computing framework for low carbon supplier selection in the beef supply chain. *J. Clean. Product.* 202, 139–149. doi: 10.1016/j.jclepro.2018.07.236

Södergren, M., McNaughton, S. A., Salmon, J., Ball, K., and Crawford, D. A. (2012). Associations between fruit and vegetable intake, leisure-time physical activity, sitting time and self-rated health among older adults: cross-sectional data from the WELL study. *BMC Public Health* 12:551. doi: 10.1186/1471-2458-12-551

Song, G., Zhang, H., Duan, H., and Xu, M. (2018). Packaging waste from food delivery in China's mega cities. *Resour. Conserv. Recycl.* 130, 226–227. doi: 10.1016/j.resconrec.2017.12.007

Sonoda, Y., Oishi, K., Chomei, Y., and Hirooka, H. (2018). How do human values influence the beef preferences of consumer segments regarding animal welfare and environmentally friendly production? *Meat Sci.* 146, 75–86. doi: 10.1016/j.meatsci.2018.07.030

Soteriades, A. D., Gonzalez-Mejia, A. M. Styles, D., Foskolos, A., Moorby, J. M., Gibbonsa, J. M. et al. (2018). Effects of high-sugar grasses and improved manure management on the environmental footprint of milk production at the farm level. *J. Clean. Product.* 202, 1241–1252. doi: 10.1016/j.jclepro.2018.08.206

Springmann, M., Wiebe, K., Mason-D'Croz, D., Rayner, M., and Scarborough P. (2018). Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *Lancet Planet Health* 2, 451–461. doi: 10.1016/S2542-5196(18)30206-7

Staelens, L., Desiere, S., Louche, C., and D'haese, M. (2018). Predicting job satisfaction and workers' intentions to leave at the bottom of the high value agricultural chain: evidence from the Ethiopian cut flower industry. *Int. J. Human Resour. Manage.* 29, 1609–1635. doi: 10.1080/09585192.2016.1253032

Steckley, M. (2016). Why 'race' matters in struggles for food sovereignty: experiences from Haiti. *Geoforum* 72, 26–29. doi: 10.1016/j.geoforum.2016.03.009

Stellingwerf, H. M., Kanellopoulos, A., van Der Vorst, J. G. A. J., and Bloemhof, J. M. (2018). Reducing CO2 emissions in temperature-controlled road transportation using the LDVRP model. *Transport. Res. Part D.* 58, 80–93. doi: 10.1016/j.trd.2017.11.008

Sulemana, I., and James, H. S. (2014). Farmer identity, ethical attitudes and environmental practices. *Ecol. Econ.* 98, 49–61. doi: 10.1016/j.ecolecon.2013.12.011

Swinton, S. M., Lupi, F., Robertson, G. P., and Hamilton, S. K. (2007). Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits. *Ecol. Econ.* 64, 245–252. doi: 10.1016/j.ecolecon.2007.09.020

Tai, A. P. K., Martin, M. V., and Heald, C. L. (2014). Threat to future global food security from climate change and ozone air pollution. *Nat. Clim. Change* 4, 817–821. doi: 10.1038/nclimate2317

Tefera, T. (2012). Post-harvest losses in African maize in the face of increasing food shortage. *Food Sec.* 4, 267–277. doi: 10.1007/s12571-012-0182-3

Tektonidis, T. G., Åkesson, A., Gigante, B., Wolk, A., and Larsson, S. C. (2015). A Mediterranean diet and risk of myocardial infarction, heart failure and stroke: a population-based cohort study. *Atherosclerosis* 243, 93–98. doi: 10.1016/j.atherosclerosis.2015.08.039

Terrapon-Pfaff, J., Gröne, M.-C., Dienst, C., and Ortiz, W. (2018a). Productive use of energy – pathway to development? reviewing the outcomes and impacts of small-scale energy projects in the global south. *Renew. Sustain. Energy Rev.* 96, 198–209. doi: 10.1016/j.rser.2018.07.016

Terrapon-Pfaff, J., Ortiz, W., Dienst, C., and Gröne, M.-C. (2018b). Energising the WEF nexus to enhance sustainable development at local level. *J. Environ. Manage.* 223, 409–416. doi: 10.1016/j.jenvman.2018.06.037

Thorlakson, T., Hainmueller, J., and Lambin, E. F. (2018). Improving environmental practices in agricultural supply chains: the role of company-led standards. *Global Environ. Change* 48, 32–42. doi: 10.1016/j.gloenvcha.2017.10.006

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philos. Trans. R. Soc. B* 365, 2853–2867. doi: 10.1098/rstb.2010.0134

Thyberg, K. L., and Tonjes, D. J. (2016). Drivers of food waste and their implications for sustainable policy development. *Resour. Conserv. Recycl.* 106, 110–123. doi: 10.1016/j.resconrec.2015.11.016

Tilman, D., Balzer, C., Hill, J., and Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. U.S.A.* 108, 20260–4. doi: 10.1073/pnas.1116437108

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature* 418, 671–677. doi: 10.1038/nature01014

Tilman, D., and Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature* 515, 518–522. doi: 10.1038/nature13959

Tozzi, L., Carballedo, A., Lavelle, G., Doolin, K., Doyle, M., Amico, F., et al. (2016). Longitudinal functional connectivity changes correlate with mood improvement after regular exercise in a dose-dependent fashion. *Eur. J. Neurosci.* 43, 1089–1096. doi: 10.1111/ejn.13222

Tregear, A. (2012). Progressing knowledge in alternative and local food networks: critical reflections and a research Agenda. *J. Rural Studies* 27, 419–430. doi: 10.1016/j.jrurstud.2011.06.003

Tscharntke, T., Klein, A., Kress, A., Steffan-Dewenter, I., and Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity-ecosystem service management. *Ecol. Lett.* 8, 857–874. doi: 10.1111/j.1461-0248.2005.00782.x

Tuomisto, H.L. (2019). The complexity of sustainable diets. *Nat. Ecol. Evolut.* 3, 720–721. doi: 10.1038/s41559-019-0875-5

Ussher, M. H., Owen, C. G., Cook, D. G., and Whincup, P. H. (2007). The relationship between physical activity, sedentary behaviour and psychological wellbeing among adolescents. *Soc. Psychiatry Psychiatr. Epidemiol.* 42, 851–856. doi: 10.1007/s00127-007-0232-x

Utter, J., Denny, S., Lucassen, M., and Dyson, B. (2016). Adolescent cooking abilities and behaviors: associations with nutrition and emotional well-being. *J. Nutri. Edu. Behavior.* 48, 35–41.e1. doi: 10.1016/j.jneb.2015.08.016

van Asselt, E. D., Noordam, M. Y., Pikkemaat, M. G., and Dorgelo, F. O. (2018). Risk-based monitoring of chemical substances in food: prioritization by decision trees. *Food Control* 93, 112–120. doi: 10.1016/j.foodcont.2018.06.001

van Dijk, W. F. A., Lokhorst, A. M., Berendse, F., and de Snoo, G. R. (2016). Factors underlying farmers' intentions to perform unsubsidised agri-environmental measures. *Land Use Policy* 59, 207–216. doi: 10.1016/j.landusepol.2016.09.003

van Holsteijn, F., and Kemna, R. (2018). Minimizing food waste by improving storage conditions in household refrigeration. *Resour. Conserv. Recycl.* 128, 25–31. doi: 10.1016/j.resconrec.2017.09.012

Veltman, K., Rotz, C. A., Chase, L., Cooper, J., Ingraham, P., Izaurralde, R. C. et al. (2018). A quantitative assessment of beneficial management practices to reduce carbon and reactive nitrogen footprints and phosphorus losses on dairy farms in the US Great Lakes region. *Agricult. Syst.* 166, 10–25. doi: 10.1016/j.agsy.2018.07.005

Venkatesh, G., Nyflött, Å., Bonnerup, C., and Lestelius, M. (2018). An economic-environmental analysis of selected barrier-coating materials used in packaging food products: a Swedish case study. *Environ. Develop. Sustain.* 20, 1483–1497. doi: 10.1007/s10668-017-9948-2

Vergé, X., Vanderzaag, A. C., Desjardins, R. L., and Mcconkey, B. (2018). Synergistic effects of complementary production systems help reduce livestock environmental burdens. *J. Clean. Product.* 200, 858–865. doi: 10.1016/j.jclepro.2018.08.016

Vermeir, I., and Verbeke, W. (2006). Sustainable food consumption: exploring the consumer "attitude – behavioral intention" gap. *J. Agricult. Environ. Ethics* 19, 169–194. doi: 10.1007/s10806-005-5485-3

Vermeulen, S. J., Campbell, B. M., and Ingram, J. S. (2012). I. Climate change and food systems. *Annu. Rev. Environ. Resour.* 37, 195–222. doi: 10.1146/annurev-environ-020411-130608

Vetter, S. H., Malin, D., Smith, P., and Hillier, J. (2018). The potential to reduce GHG emissions in egg production using a GHG calculator – a cool farm tool case study. *J. Clean. Product.* 202, 1068–1076. doi: 10.1016/j.jclepro.2018.08.199

Vogt, R., and Kaiser, L. (2008). Still a time to act: a review of institutional marketing of regionally-grown food. *Agricult. Human Values* 25, 241–255. doi: 10.1007/s10460-007-9106-9

Ward, P. R., Verity, F., Carter, P., Tsourtos, G., Coveney, J., and Wong, K.C. (2013). Food stress in adelaide: the relationship between low income and the affordability of healthy food. *J. Environ. Pub. Health* 2013:968078. doi: 10.1155/2013/968078

Welch, R. M., and Graham, R. D. (1999). A new paradigm for world agriculture: meeting human needs productive, sustainable, nutritious. *Field Crops Res.* 60, 1–10. doi: 10.1016/S0378-4290(98)00129-4

West, P. C., Gerber, J. S., Engstrom, P. M., Mueller, N. D., Brauman, K. A., Carlson, K. M., et al. (2014). Leverage points for improving global food security and the environment. *Science* 345, 325–328. doi: 10.1126/science.1246067

Westermann, O., Förch, W., Thornton, P., Körner, J., Cramer, L., and Campbell, B. (2018). Scaling up agricultural interventions: case studies of climate-smart agriculture. *Agricult. Syst.* 165, 283–293. doi: 10.1016/j.agsy.2018.07.007

Wheeler, T., and von Braun, J. (2013). Climate change impacts on global food security. *Science* 341, 508–513. doi: 10.1126/science.1239402

Wilkins, J. (2005). Eating right here: moving from consumer to food citizen. *Agricult. Human Values* 22, 269–273. doi: 10.1007/s10460-005-6042-4

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Wittman, H., Dennis, J., and Pritchard, H. (2017). Beyond the market? New agrarianism and cooperative farmland access in North America. *J. Rural Studies* 53, 303–316. doi: 10.1016/j.jrurstud.2017.03.007

Wood, G., and Newborough, M. (2003). Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. *Energy Build.* 35, 821–841. doi: 10.1016/S0378-7788(02)00241-4

Zanoni, S., and Zavanella, L. (2012). Chilled or frozen? decision strategies for sustainable food supply chains. *Int. J. Product. Econ.* 140, 731–736. doi: 10.1016/j.ijpe.2011.04.028

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 26 June 2020
doi: 10.3389/fsufs.2020.00093

Using Input-Output Analysis to Measure Healthy, Sustainable Food Systems

Sinead M. Boylan [1,2,3]*, *Anne-Marie Thow* [1,3], *Elijah K. Tyedmers* [4], *Arunima Malik* [4,5], *Janet Salem* [4,6], *Robyn Alders* [7,8], *David Raubenheimer* [2,3] *and Manfred Lenzen* [4]

[1] School of Public Health, University of Sydney, Sydney, NSW, Australia, [2] School of Life and Environmental Sciences, University of Sydney, Sydney, NSW, Australia, [3] Charles Perkins Centre, University of Sydney, Sydney, NSW, Australia, [4] ISA, School of Physics, University of Sydney, Sydney, NSW, Australia, [5] Business School, University of Sydney, Sydney, NSW, Australia, [6] Asia and the Pacific Office, United Nations Environment Programme, Bangkok, Thailand, [7] Kyeema Foundation, Brisbane, QLD, Australia, [8] Centre for Global Health Security, Chatham House, London, United Kingdom

OPEN ACCESS

Edited by:
Selena Ahmed, Montana State University, United States

Reviewed by:
Aida Turrini, Consiglio per la Ricerca in Agricoltura e L'analisi Dell'Economia Agraria (CREA), Italy
Janet Louise Weber, Massey University, New Zealand

***Correspondence:**
Sinead M. Boylan
sinead.boylan@sydney.edu.au

Specialty section:
This article was submitted to Nutrition and Sustainable Diets, a section of the journal Frontiers in Sustainable Food Systems

Received: *09 July 2019*
Accepted: *22 May 2020*
Published: *26 June 2020*

Citation:
Boylan SM, Thow A-M, Tyedmers EK, Malik A, Salem J, Alders R, Raubenheimer D and Lenzen M (2020) Using Input-Output Analysis to Measure Healthy, Sustainable Food Systems. Front. Sustain. Food Syst. 4:93. doi: 10.3389/fsufs.2020.00093

Our current food systems are hampering efforts to meet the Sustainable Development Goals. Reshaping our food systems could have enormous co-benefits for our populations and planet. However, decision makers and experts are questioning whether it is possible to meet environmental, social and economic goals simultaneously, or whether tradeoffs are necessary. There has been a call for the development of better measurements and indicators to help policymakers understand the benefits and considerations for healthy and sustainable food systems. There is an urgent need to address the gaps in understanding of what a sustainable food system means across varying populations and geographies and how we can better measure these systems. Practice calls for a framework in which different aspects of food and nutrition security can be measured under identical scope, where policy simulations which arrive at multi-indicator outcomes are comparable, and where quantified trade-offs between different sustainable development objectives are valid. We introduce, and focus on one technique that does allow such multi-indicator scope-consistent analysis of food systems under a life-cycle perspective: input-output analysis. We describe input-output analysis, and its relevance and advantages for measuring the sustainability of food systems, nutrition and diets, including resilience and vulnerability. Using data from the global multi-regional input-output databases, we then describe potential measures that are able to extend the current state of art into a more comprehensive framework that has the potential to support policy related to global initiatives such as the Sustainable Development Goals.

Keywords: sustainability, food systems, diet, indicator, measurement, nutrition security

INTRODUCTION

Food systems encompass a range of actors and activities involved in the production, aggregation, processing, distribution, consumption, and disposal of food products (Food and Agriculture Organisation, 2018). Food systems underpin the 2030 Agenda for Sustainable Development, also known as the Sustainable Development Goals (SDGs), which is a global commitment to eradicate poverty and hunger while ensuring environmental sustainability, health and prosperity for all (United Nations, 2015). Food and agriculture are associated with most of the 17 goals, with Goal two specifically devoted to ending hunger and malnutrition, achieve food security and improved nutrition and promote sustainable agriculture (United Nations, 2015). Over millennia, our food systems have evolved from highly localized systems, to an international system; today, the food we grow, harvest, process, trade, transport, store, sell and eat is a connecting thread along value chains between people, prosperity, and planet (United Nations Environment Programme, 2016).

Food systems are rapidly changing, growing in volume and intensity while still operating within the same planetary boundaries. It has been estimated that the world needs to produce 70% more food to feed the 9 billion people who will live on this planet in 2050 (Food and Agriculture Organisation, 2009). While the ability to currently produce enough food for all remains largely unquestioned, the ability to produce enough food to equitably and efficiently feed the world without harming population or planetary health remains uncertain. The global food system fails to meet the related challenges of sustainability, health, vulnerability, and resilience. The way in which food systems currently operate are responsible for land degradation, depletion of fish stocks, nutrient losses, impacts on terrestrial and aquatic biodiversity, impacts on air, soil and water quality, and greenhouse gas emissions contributing to climate change (United Nations Environment Programme, 2016). The expected population growth, expansion of cities, dietary shifts to unhealthy and unsustainable consumption will increase the pressures even more.

While food production has more than doubled and diets have become more varied (and more energy-dense) as global incomes increase, over 800 million people are still hungry, over 2 billion suffer from micronutrient deficiencies (in particular of iron, zinc, vitamin A, and iodine) and over 2 billion people are overweight or obese (United Nations Environment Programme, 2016).

Tackling food systems challenges will require an integrated approach if we are to meet many of the SDGs (United Nations Development Programme, 2018), with research indicating that reshaping our food systems could not only help reach global greenhouse gas emission targets for 2050 plus other environmental wins, but protect and improve population health (Friel et al., 2009). Public and private sector actors globally are taking action to shift toward healthy and sustainable food systems.

But what exactly is a healthy and sustainable food system, and would the proposed solutions actually work? The FAO describe "sustainable diets" as *"those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources"* (Food and Agriculture Organisation and Bioversity International, 2010). While this definition is concerned with "diets," it suggests that "diets" cannot be separated from the food system, and moreover, from human and ecosystem health. It also highlights that if food systems are to help meet the SDGs, using traditional nutritional science and indicators will not be enough.

There has been a call for better measurements and indicators to be developed to help policymakers understand the benefits, possible unintended consequences and other considerations (e.g., data availability and complexity), for healthy and sustainable food systems (United Nations Standing Committee on Nutrition, 2017; Tuomisto, 2019). In order to advance commitments to sustainable food systems and, moreover, the SDGs, there is an urgent need to address the gaps in understanding of what a sustainable food system means across varying populations and geographies and how we can better measure these systems. An integrated approach underpinned by transdisciplinary research is key (Francis et al., 2008; Mendez et al., 2013; Clancy, 2017).

Aim of This Work

We will demonstrate how input-output analysis (IOA), which is a technique that draws on a global life-cycle perspective, can be used to effectively advance metrics regarding healthy and sustainable food systems. To do this, we have conducted a mapping review to map out existing literature, identify gaps in research and highlight the strengths of IOA in advancing metrics. We will also present example indicators using IOA to illustrate its power and relevance.

PRIOR WORK TO MEASURE HEALTHY AND SUSTAINABLE "DIETS"

Increasing research has focused on the impact of the food system on environmental sustainability, in particular greenhouse gas emissions (GHGEs) and in some cases, land use (Ridoutt et al., 2017). However, the key determinants, components and processes of a sustainable diet remain largely overlooked. These include use of fossil fuels, trade, food subsidies, water use, packaging material, gender, and knowledge to name but a few. Achieving healthy and sustainable diets for all will require a sustained effort across geographies, sectors and disciplines. In recent years, there have been a number of attempts to consider a comprehensive range of indicators at regional (World Wildlife Federation, 2013) and global levels (Chaudhary et al., 2018; Willett et al., 2019).

The World Wildlife Fund Live Well for Life project defined sustainable diets for France, Sweden and Spain (World Wildlife Federation, 2013). This project collected data on consumption patterns, nutritional recommendations, dietary guidance, GHGEs associated with particular foods, and general price information. They demonstrated that for all three countries a healthy and sustainable diet (one that complies with nutritional recommendations, reduces GHGEs by 25%, and provides an acceptable choice of foodstuffs) is possible and is not too far from current consumption patterns. However, the authors report a number of methodological limitations and recommend better GHGEs and life-cycle analysis (LCA) data, more research into reducing GHGEs in production and distribution of food and into the consequences of taking wider sustainability criteria (water, biodiversity) into account.

More recently, The EAT-Lancet Commission, have led the development of global scientific targets for sustainable food systems (Willett et al., 2019). The focus is on food production and consumption, with a healthy reference diet integrated with a set of system-wide environmental parameters based on the planetary boundaries framework (Stockholm Reslience Centre, 2018). The findings of this Commission indicate that a healthy food system is achievable with major dietary shifts, large reductions in food waste and loss, and major improvements in food production practices. The Commission acknowledges that other parts of the food system were not considered as part of this assessment, nor were issues around economy, culture and society. The Commission states that interdisciplinary research and monitoring with replicable methodology at national and other levels is urgently needed to help policy actors to operate on a strong evidence base.

Chaudhary et al. (2018) have partly considered several important determinants in their application of seven indicators, including socio-cultural well-being and resilience, across 156 countries (Chaudhary et al., 2018). However, there are a number of ways in which this multi-indicator assessment could be strengthened. Indicators in this analysis were not measured and reported with the same scope, because some indicators were measured in a supply-chain context, whilst others were not (e.g., well-being). Further, their measurement of food consumption was based on Food Balance Sheet data and was analyzed using a single food composition database. Food Balance Sheet data do not necessarily reflect actual intakes and ideally, up-to-date country-specific food composition data would be included in this analysis (de Bruyn et al., 2016).

Our current global economy is increasingly linked through an international supply-chain network that accounts for around 30% of major environmental and social impacts (Wiedmann and Lenzen, 2018). The pressure on ecosystems and natural resources from food supply chains will increase with the expected increase in demand in both volume from population growth, as well as intensity from dietary shifts toward more resource-intensive products (e.g., livestock-based food and processed food and drinks) that are associated with increased incomes. Climate change will further exacerbate these issues (United Nations Environment Programme, 2016). Today's food systems in particular predominantly consist of highly industrial globalized supply chains and so in measuring the health consequences and sustainability of these systems, international trade and the global supply-chain network must be considered. Herein lies an important limitation of previous research (Chaudhary et al., 2018; Willett et al., 2019) as we now detail.

ADVANCING THE MEASUREMENT OF HEALTHY AND SUSTAINABLE "DIETS"

The Importance of a Global Life-Cycle Perspective

Whilst in the analysis by Chaudhary et al. (2018), carbon, water, land and biodiversity were measured with a supply-chain coverage (or in other words, as footprints, **Figure 2** in Chaudhary et al.), other indicators such as nutrient adequacy, affordability, well-being, and safety were not (Chaudhary et al., 2018). This is because they cannot be measured in a life-cycle context, either because they have no supply-chain relevance (e.g., affordability is relevant only to the consumer in their analysis), because they are not additive (a key requirement in LCA e.g., one cannot add quantities measured as ratios or indices), or not industry-specific quantities (e.g., most surveys measure well-being as a region- but not industry-specific quantity).

Mixing quantities that are measured under a life-cycle or footprint scope with others that are not, means that trade-offs and relationships between the different indicators can in general not be established (this circumstance is explained in Lenzen et al. for the example of a deficient environmental impact statement; Lenzen et al., 2003). This shortcoming is the reason why practice calls for a framework in which different aspects of food and nutrition security can be measured under identical scope, where policy simulations which arrive at multi-indicator outcomes are comparable, and where quantified trade-offs between different sustainable development objectives are valid. In the following we will therefore introduce, and focus on IOA, as one technique that does allow such multi-indicator scope-consistent analysis of food systems under a life-cycle perspective.

Further, given that food and nutrition sustainability are a global problem, a research framework is needed that:

a) allows modeling of international trade and the global supply-chain network,
b) provides completely harmonized physical and economic data at the global scale and at the detail of individual economic sectors, and
c) is governed by accepted worldwide standards.

IOA can address each of these components and thus offers a suitable approach in researching the complexities of healthy and sustainable food systems at a global level. We will now outline example studies from the current literature followed by a discussion of potential measures, namely: the social and environmental impacts of food demand; vulnerability; local disasters, global reach; resilience; fiscal measures and income distribution; the supply chain of foods associated with chronic disease risk; and trade, inequality and food insecurity.

Input-Output Approaches to Measuring the Sustainability of Food Systems

Input-output analysis (IOA) is an economic technique conceived in the 1930s by Nobel Prize Laureate Wassily Leontief 1936 (Leontief, 1936). IOA is able to interrogate economic data on inter-industry transactions, final consumption and value added, in order to trace economic activity rippling throughout complex supply-chain networks and unveil both immediate and indirect impacts of systemic shocks (Leontief, 1966). Over the past 70 years, IOA has been used extensively for a wide range of public policy and scientific research questions (Rose and Miernyk, 1989). In the past two decades IOA has experienced a surge in applications, especially on carbon footprints (Wiedmann, 2009) and global value chains (Timmer et al., 2014), and in the disciplines of LCA (Suh and Nakamura, 2007) and Industrial Ecology (Suh, 2009).

International and inter-industry trade modeling is typically undertaken on the basis of global multi-regional input-output (MRIO) databases (Tukker and Dietzenbacher, 2013). These databases are based on a range of data sources: national input-output tables published by numerous national statistical agencies such as the Australian Bureau of Statistics (Australian Bureau of Statistics, 2016a), international trade and national accounts data published by the United Nations (United Nations Industrial Development Organisation, 2016; United Nations Statistics Division, 2016a,b,c,d, 2017a), and economic data published by a range of other global governance organizations (SourceOECD, 2009; Institute of Developing Economies-Japan External Trade Organisation, 2015; International Food Policy Research Institute, 2015; Organisation for Economic Co-operation Development, 2015; World Bank, 2017). Input-output accounts are governed by established United Nations (United Nations, 1999, 2009), European (Eurostat, 2016) and national (Australian Bureau of Statistics, 2016b) data standards. Monetary national and trade accounts are seamlessly integrated and harmonized with satellite accounts for physical (economic, social and environmental sustainable development) indicators such as employment, income, gender and income equality, occupational safety, GHGEs, water scarcity, land degradation, air pollution, nitrogen emissions, energy use, biodiversity decline, and material flow, amongst others. This integration and harmonization is standardized in the System of Environmental-Economic Accounting (United Nations Statistics Division, 2017b).

Some of the authors of the present paper are members of a research team with expertise in global MRIO database compilation and use. In particular, the authors have utilized Australian Government-funded NeCTAR Virtual Laboratory eResearch technology (NeCTAR, 2013) to develop the Global MRIO Virtual Lab. The data used to produce the exemplary results presented in this paper were compiled in the Global MRIO Lab. MRIO databases also exist at the sub-national inter-regional level.

Example Studies From the Literature

The potential of IOA lies in its ability to account for the complex interactions between economic, social and environmental factors that both shape food systems and arise from food systems. Kytzia et al. (2004) highlight the shortcomings of several analytical methods including LCA, material flow analysis (MFA) and IOA, but suggest using a hybrid model of IOA and MFA based on an intrinsic aspect of IOA—money flow (Kytzia et al., 2004). Through a comparative evaluation of the environmental impact between different vegetarian diets in Switzerland, it was demonstrated that although a plant-based diet has environmental benefits, it was not a viable option within the context of the Swiss economy. Similarly, a review in the United States indicated that current food systems may not be capable of supporting an increase in consumption of fruits and vegetables (Finley et al., 2017). These findings demonstrate that current food systems can be constrained by a sustainability threshold in a sense meaning that a "conventionally" sustainable diet, such as a vegetarian one, may only be a more sustainable option until that threshold is reached (such as an entire country shifting to a vegetarian diet). In these cases, importing more fruits and vegetables to satisfy demand could negate the environmental benefits of a vegetarian diet due to the embodied environmental impact associated with importing.

The support for plant-based or low-meat diets and their benefits for planetary health stem from the consensus that a reduction in meat consumption would significantly reduce GHGEs (United Nations Environment Programme, 2016). However, this does not imply that plant-based diets do not contribute their share of GHGEs as well, and the impact embodied along the entire supply chain should be taken into consideration. An input-output study done by Hirst (1974) aiming to determine the energy embodied in food-related sectors found the transport and processing sectors to be most energy intensive and thus a noticeable difference existed between fresh and processed fruits and vegetables (Hirst, 1974). The larger environmental impact embodied in processed fruits and vegetables further emphasizes the need for a more sustainable food system as opposed to simply switching to what are considered more sustainable diets. An evaluation of GHGE contributors from food-related sectors also underlined plant-related agriculture as a significant producer of N_2O—a contributor to GHGEs (Kramer et al., 1999). These studies highlight that examining the health and sustainability of food systems using a food-based approach can obscure the complexities of such systems.

Organic farming methods have been suggested as an effective measure against N_2O emissions released from fertilizer use. A study conducted by Wood et al. (2006) compared organic and conventional methods of farming. The on-site impacts of both farming methods were similar at first glance, however the differences were highlighted further across the supply chain indicating that organic farming tended to have a lesser impact overall. Australian research using LCA has shown that industrial food production systems for chicken meat and lettuce can be more environmentally sustainable than alternative commercial and civic systems, indicating the importance of multiple food subsystems for food security (James and Friel, 2015).

These food systems must also be tailored (and therefore, monitored) according to regional and cultural circumstances (Behrens et al., 2017). MRIO was used to evaluate the environmental impact of nationally recommended diets compared to national average diets (Behrens et al., 2017). The findings indicate that the environmental impact was significantly reduced in higher-income countries, slightly reduced in middle-income countries and had an increased impact in low-income countries when comparing nationally recommended diets to average diets. While this may be largely due to the higher environmental impact of diets in higher-income countries, there are other explanations for these findings. Different regions place different levels of importance on different nutrients and foods, reflecting local agroecological conditions and their ability to adequately nourish humans. The findings also indicate that there is room to improve nationally recommended diets to support healthy and sustainable food systems. From the literature so far, it is evident that IOA has helped with understanding that a sustainable diet may not necessarily be a part of a sustainable food system, and a sustainable food system in one context may not necessarily be sustainable in another.

Example Indicators Using IOA

IOA can support the measurement of food system impact with respect to sustainability and nutrition. The notion of sustainable food systems can potentially include a very broad set of objectives and performance indicators, and as a consequence a very extensive range of methods and applications, even when the scope is restricted to IOA. Here, we do not aim to present an exhaustive account of potential measures, but instead we will just present seven examples to illustrate the power and relevance of IOA for practice.

Social and Environmental Impacts of Food Demand

The most straightforward application of IOA for measuring the sustainability of diets is as a conventional LCA of the environmental and social impact of food consumption. Technically, this involves arranging physical indicator data (such as quantities of water use, greenhouse gas emissions, employment etc.) into so-called satellite accounts (Bartelmus et al., 1991; United Nations Statistics Division, 2017a), then applying Leontief's physically extended demand-pull calculus (Leontief and Ford, 1970), and calculating so-called multipliers for each satellite indicator (International Food Policy Research Institute, 2015). These multipliers quantify the amount of indicator quantity that is associated with a monetary unit of final demand of commodities. Multipliers cover impacts across the entire upstream supply-chain network, or life cycle, of commodities.

Figure 1 shows multipliers for a range of American food products, in terms of seven environmental and social indicators. The information is taken from a number of publications [employment (Alsamawi et al., 2014a); GHGEs (Malik et al., 2016); energy use (Lan et al., 2016); land (Moran et al., 2013); Nitrogen emissions (Oita et al., 2016); water scarcity (Lenzen et al., 2013)].

The indicator list can be extended to cover other indicators such as human health (Gill, 2006; Capon and Dannenberg, 2016), hunger (Pritchard, 2012), soil degradation (Lal et al., 1997; McBratney et al., 2003, 2017a,b; Koch et al., 2013), air pollutants (Kanemoto et al., 2014), occupational hazards (Alsamawi et al., 2017), child labor (Gómez-Paredes et al., 2016), gender and income inequality (Alsamawi et al., 2014b), corruption (Xiao et al., 2017a), biodiversity loss (Lenzen et al., 2012), material flow (Wiedmann et al., 2015), and many more (Xiao et al., 2017b). Using the Global MRIO Lab (Lenzen et al., 2017), this analysis can also be carried out for any year between 1990 and 2015, and for 220 countries.

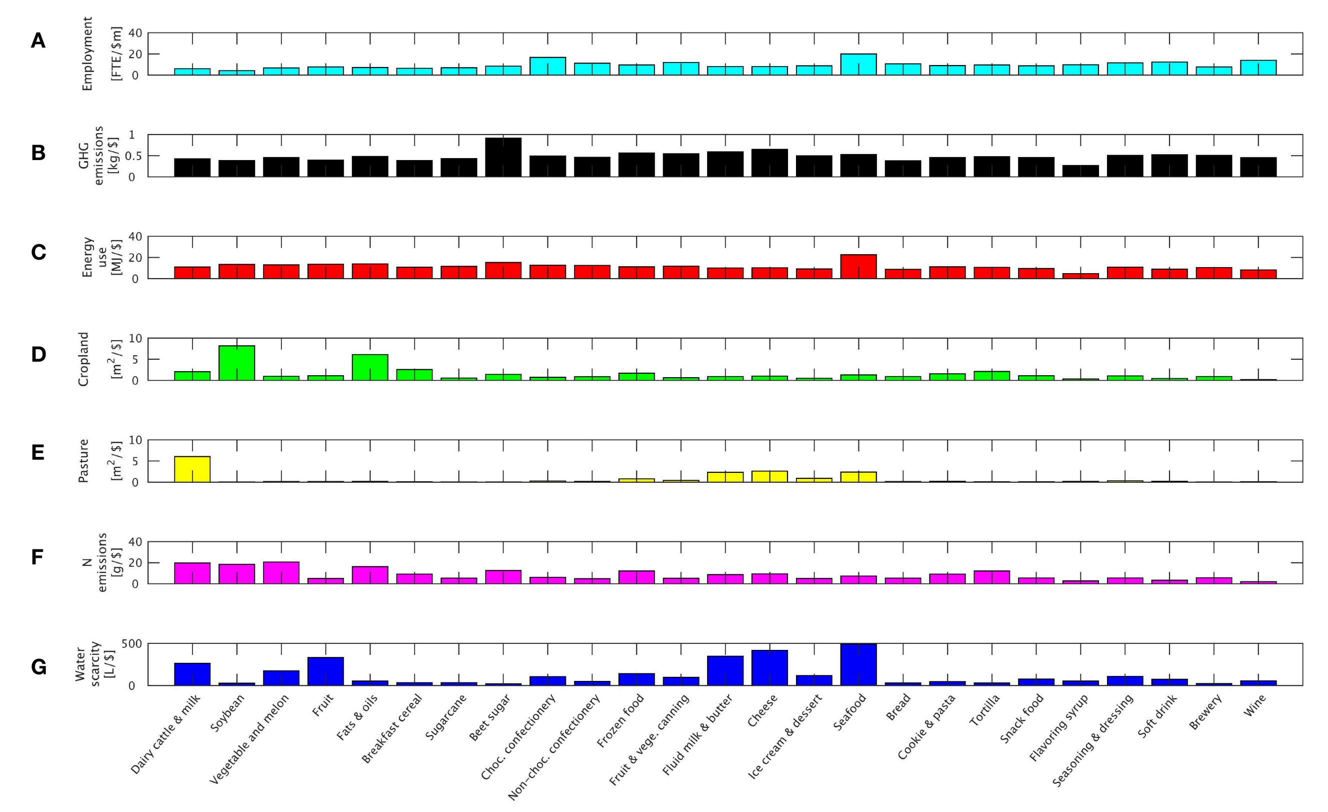


FIGURE 1 | Multipliers for a range of US food products. Multipliers for a range of US food products, in terms of 7 environmental and social indicators, per unit of US$ of household expenditure. FTE, Full-time equivalent; GHG, greenhouse gas; MJ, megajoule; N, nitrogen. Social multiplier is shown in **(A)**, and environmental multipliers in **(B–G)**.

Multipliers can be compared, and trade-offs between them established, because they are calculated with identical scope.

Another way of exploring the social and environmental impacts, could be to examine food consumption data, rather than food demand data, however this is outside the scope of this current paper.

Vulnerability: Global Food Hinterlands

The technique applied in the previous example can be extended from individual commodities to the food consumption of entire countries. Such applications yield what is commonly referred to as "resource hinterlands" (Lenzen and Peters, 2010). In this context, vulnerability is of particular interest, and a low degree of vulnerability can be seen as a prerequisite of food or diet sustainability. National food systems are vulnerable to adverse events within but also beyond their borders. In order to understand these vulnerabilities, it is helpful to understand the "global hinterland" of a country's food consumption. In other words: where does the food that a country consumes come from? And in addition, where do non-food items that are needed for food production (e.g., agricultural machinery, pesticides, fertilizer) and their supply-chain inputs (e.g., steel, chemicals etc.) come from? Answering these questions requires a complete global LCA of food consumption.

Using MRIO analysis, we find that the global food hinterlands of the USA, Germany, Japan and Australia span most high-income countries, predominantly in North America, Europe and Asia, and leave out South America and Africa. Transport distances seem to play some role as the USA relies more on Canada than other countries, Japan relies more on China, and Germany more on the EU. Interestingly, Brazil's food hinterland is concentrated on Argentina and the USA, whilst India relies mostly on its own food production (**Figure 2**). All six countries represent a more important food source for themselves than their import origins.

Smaller and/or less populous countries face more complex food supply realities (**Figure 3**). Unlike the six countries shown in **Figure 2**, some countries rely heavily on food imports from abroad. For example, Canada is highly dependent just on the USA, and New Zealand on Australia. Norway relies on a broader set of countries, as its own food production is relatively small due to climatic conditions. An extreme case are small-island nations such as Palau, which rely almost entirely on food imports from around the world. Cuba is seen as relatively self-sufficient because of political circumstances. The Central African Republic has a negligible global food hinterland, given that the country is amongst the poorest on the planet, and cannot afford expensive imported food.

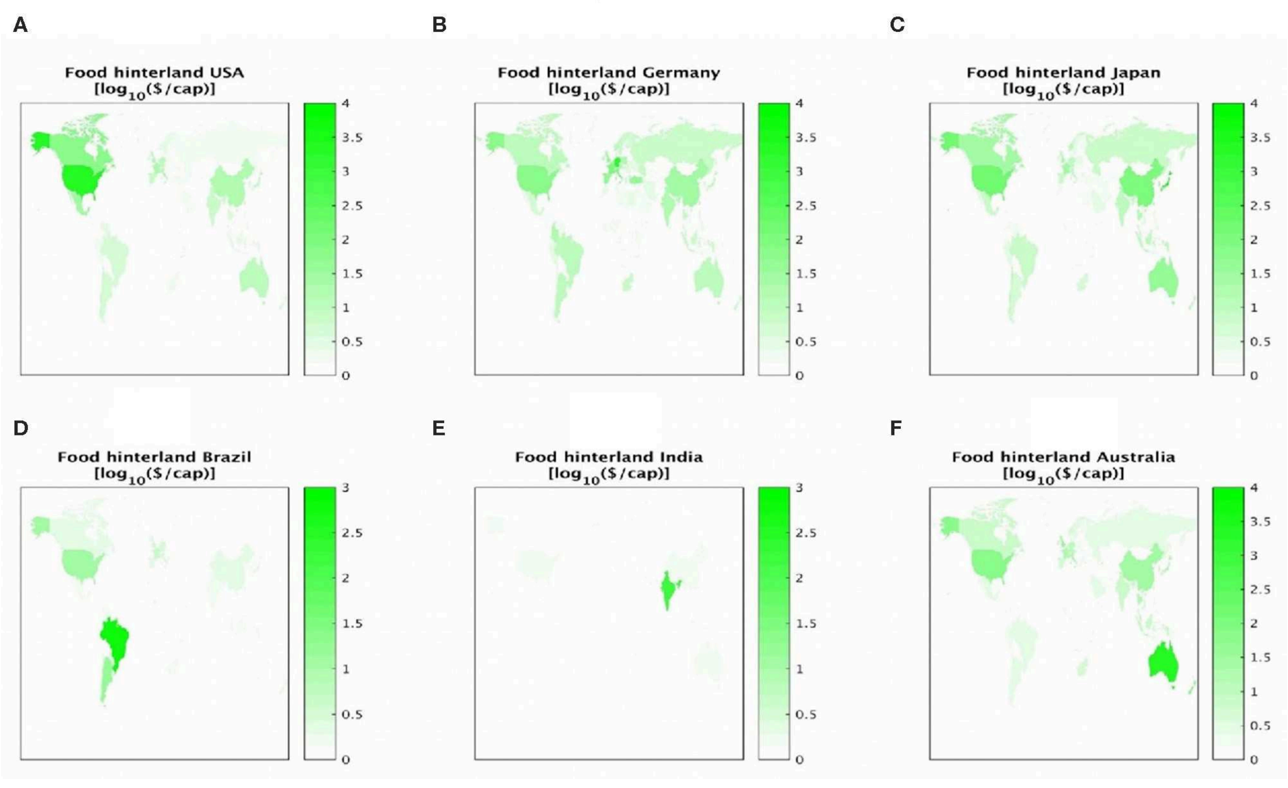


FIGURE 2 | Global food hinterlands of countries with high populations. Global food hinterlands of the USA **(A)**, Germany **(B)**, Japan **(C)**, Brazil **(D)**, India **(E)**, and Australia **(F)**. To relate the production values to population size in the consuming countries, the maps are color-coded in units of $\log_{10}$ (US$/cap), so that e.g., 3 = US$1,000/cap.

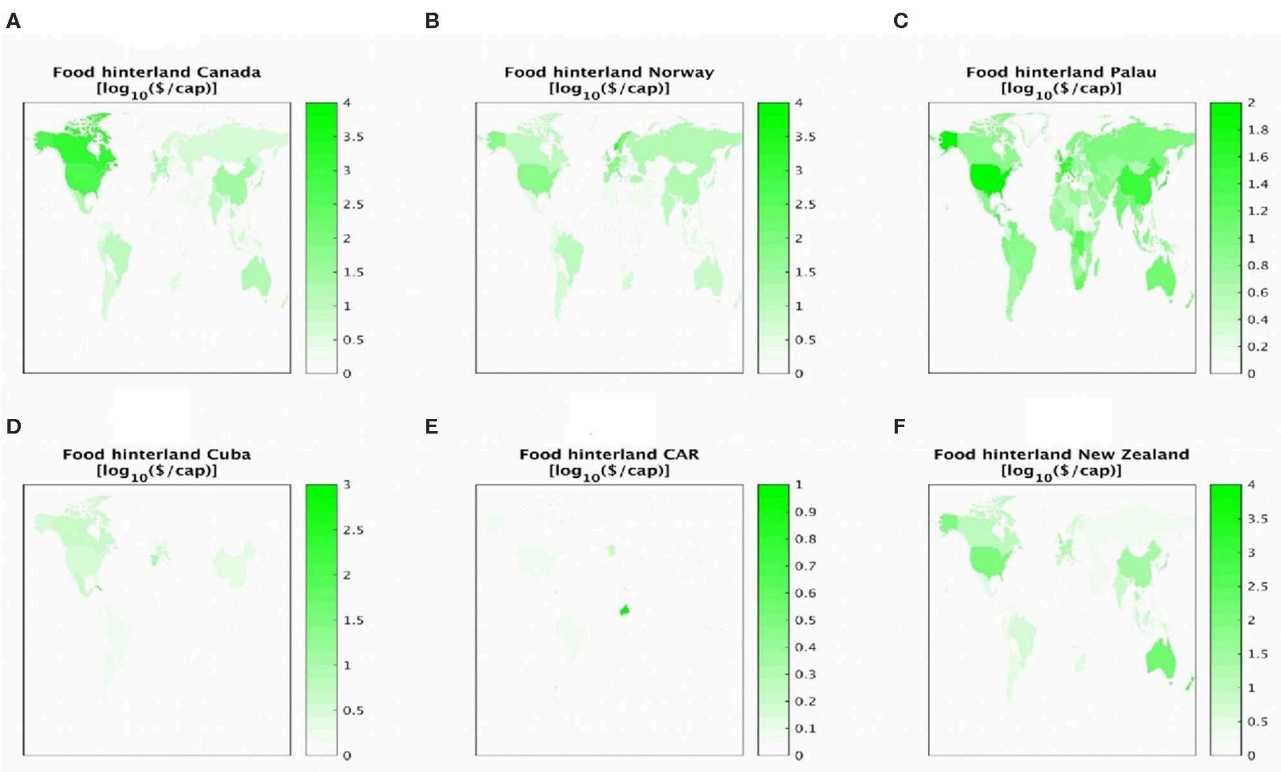


FIGURE 3 | Global food hinterlands of countries with low populations. Global food hinterlands of Canada **(A)**, Norway **(B)**, Palau **(C)**, Cuba **(D)**, the Central African Republic (CAR) **(E)**, and New Zealand **(F)**. To relate the production values to population size in the consuming countries, the maps are color-coded in units of $\log_{10}$ (US$/cap), so that e.g., 3 = US$1,000/cap.

TABLE 1 | Exports of wheat, rice, corn and soybeans from six export origins, as a percentage of total world exports.

	Wheat	Rice	Corn	Soybeans
% of total world exports				
Australia	10	0.8	-	-
Argentina	5	6	15	1.2
Brazil	-	1.4	13	37
India	-	29	-	0.2
Russia	12	-	3	0.3
USA	15	10	36	44
Sum of 6	42	47.2	67	82.7

Local Disasters, Global Reach

Vulnerabilities play out in disasters. In the context of food supply and diets, six countries in the world supply almost half, or more than half of global exports of four of the world's most important staple crops: rice, wheat, soybeans and corn (**Table 1**).

Many of these crop systems are vulnerable to natural disasters such as floods, droughts and storms, or human-induced disasters such as chemical pollution, invasive species, or civil unrest. Any adverse event that destroyed a sizable fraction of national crops would lead to production shortfalls. For example, in 2007 when extreme weather hit the Murray-Darling Basin in Australia, the fall in cereal production was partly to blame for soaring food prices globally (Piesse and Thirtle, 2009). It is very likely that markets will respond by fulfilling local needs at the expense of international markets (particularly when the domestic market is relatively high-income, as in Australia). Accordingly, we have modeled the global production impacts of a 10% decrease of exports of wheat, rice, corn and soy beans from Australia, Argentina, Brazil, India, Russia and the USA (**Figure 4**).

Shocks to staple exports from the USA would have a major global reach (**Figure 4**, top left panel). In particular, Canadian consumers would feel an impact in the order of US$100 per capita. Similar relationships exist between Brazilian recipients of Argentinian crops (bottom left), and Kazakh recipients of Russian crops (top right). The disaster reach originating from India, Brazil and Australia is about one order of magnitude smaller.

Interestingly, exporting countries are themselves affected by the shock, even though we have assumed that local supplies remain unaffected. This is because countries rely on imports of processed products that were initially made out of the crop they exported. For example, Australia may import American wheat products made from Australian wheat. If Australian wheat exports to the USA decreased, some of the US food exports to Australia would be affected.

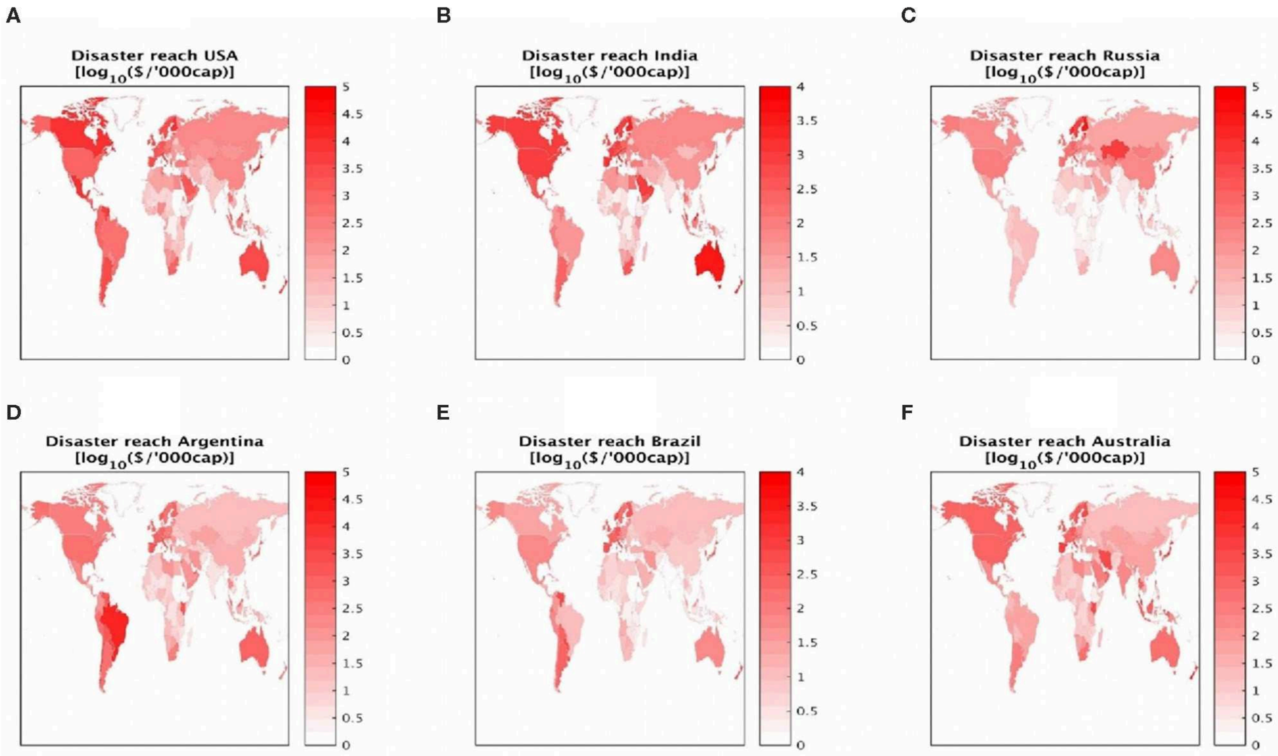


FIGURE 4 | Export shortfalls and global production. Decrease in global production as a result of a 10% shortfall in exports of wheat, maize, rice and soybeans from six major exporters: USA **(A)**, India **(B)**, Russia **(C)**, Argentina **(D)**, Brazil **(E)**, Australia **(F)**. The decrease of 10% was chosen only to exemplify the impacts and is not based on any predicted scenarios. To relate the production losses to population size in the producing countries, the maps are color-coded in units of $\log_{10}$ (US$/'000cap), so that e.g., 5 = US$100/cap.

Resilience

Rose (2017) defines economic resilience as the ability of individuals and communities to inherently and adaptively respond to hazards, and to avoid potential losses (Rose, 2017). Measuring resilience allows evaluating disaster responses and identifying strategies for reducing losses. In an IO context, individuals, communities, companies, cities and regions are all exposed to risks stemming from the exposure of their supply chains to potential disasters, and thus supply-chain resilience forms an important part of the economic resilience concept. In IO parlance, a low degree of vulnerability is one characteristic of a resilient economy (Rose, 2011). Resilience in the face of global adversity is also an important concept in relation to food and nutrition security (Food and Agriculture Organisation, 2013; Berry et al., 2015; Candy et al., 2015; MacMahon et al., 2015; Tendall et al., 2015) and therefore for the sustainability of food systems. A coherent analytical modeling framework that integrates food security, sustainability and resilience is required for improving our understanding of indirect effects of climate change-related impacts, thus informing effective decision-making for adaptation of food systems (Wheeler and von Braun, 2013).

Resilience is also traditionally dealt with quantitatively within IOA (Rose, 2007, 2011; Cox et al., 2011; Rose and Krausmann, 2013; Chen et al., 2017). One example for addressing resilience against disasters is to re-structure inter-industry and inter-regional trade (e.g., by choosing alternative suppliers and/or supply chains), with the aim of reducing the exposure to disaster-prone or environmentally intensive commodity origins (Burch and Pritchard, 1996; Venn et al., 2006; Ash and Newth, 2007; Holloway et al., 2007; Maye et al., 2007; Kneafsey et al., 2008). Often, linear programming techniques are used for this purpose (Muller, 1973; James and Musgrove, 1986; Tamiz et al., 1998; Kondo and Nakamura, 2005; Lin, 2011).

Fiscal Measures and Income Distribution

IOA can also be used effectively to measure the intended and unintended consequences of policy intervention to promote healthy and sustainable food systems, by assessing the impact of consumer-oriented interventions on the global food system. For example, fiscal policy interventions have been widely recommended as effective interventions to incentivize dietary change among consumers (Thow et al., 2018). These interventions work by creating price differentials that favor the consumption of sustainable (environment- or health-wise) commodities (Bonnet and Réquillart, 2013; Edjabou and Smed, 2013; Härkänen et al., 2014; Bíró, 2015; Hagenaars et al., 2017; Harding and Lovenheim, 2017; Nomaguchi et al., 2017; The Lancet Diabetes and Endocrinology, 2017; The Lancet Public Health, 2017). While much existing evidence is specific to a given national context (for example the UK, Chile, Denmark or Hungary), it is possible to assess global impacts of a commodity-specific tax using a time series of global MRIO databases that covers 220 countries. For example, it is possible to assess the wage impacts on sugar producers and manufacturers of commodities high in sugar (**Figure 5**). Due to the geographical location of these producers, low-income countries will be most significantly affected, highlighting the challenge in balancing environmental, health, social and economic wins.

A key benefit of IOA in this context is the ability to examine the complexity of the supply chains relevant to the taxed products. It can thus provide forewarning about potential economic impacts so that governments and industry can pro-actively develop strategies to mitigate the impact. The adaptability of employment across sectors, and the shift in consumption to other goods or services (which in some cases may be more employment intensive), mean that aggregate employment as well as sectoral employment needs to be considered. Two recent studies have indicated that taxes on sugar sweetened beverages, for example, are unlikely to have negative effects on aggregate employment, and may also have positive impacts through the employment-generating impacts of revenue and reallocation of consumer expenditure (Powell et al., 2014; Guerrero-López et al., 2017). The ability of industry to adapt to emerging trends also needs to be considered—including a significant global trend toward "health" products in the food sector, which nuts are very well-positioned to take advantage of. This type of research would be equally applicable to a range of other policy interventions that have been tabled in the United Nations, such as removal of harmful subsidies, investment in sustainable food system research or consumption-oriented policies such as stricter marketing rules for unhealthy food.

The Supply Chains of Foods Associated With Chronic Disease Risk

As concern regarding the high burden of diet-related non-communicable diseases (NCDs) grows, more and more governments are taking action through the implementation of policies designed to reduce consumption of foods high in fat, salt and sugar, which are associated with NCD risk (World Cancer Research Fund, 2018). Such strategies include labeling, restrictions on marketing, health promotion campaigns and fiscal policy intervention. Public health evidence suggests that reductions in consumption of these foods would have significant benefits for both health and environmental sustainability, if consumers of high animal-sourced diets switch to a more plant-based diet. However, these products incorporate other ingredients as well. IOA can be used to assess the impacts of reduction in consumption of a food high in salt, fat and/or sugar not only on the production of the intended target, as we show above with a tax on sugar, but also on the other—in some cases healthy—commodities also involved in their production. A decline in the consumption of chocolate, e.g., will affect the production of cocoa upstream in chocolate's supply chains and associated employment in low-income countries, even

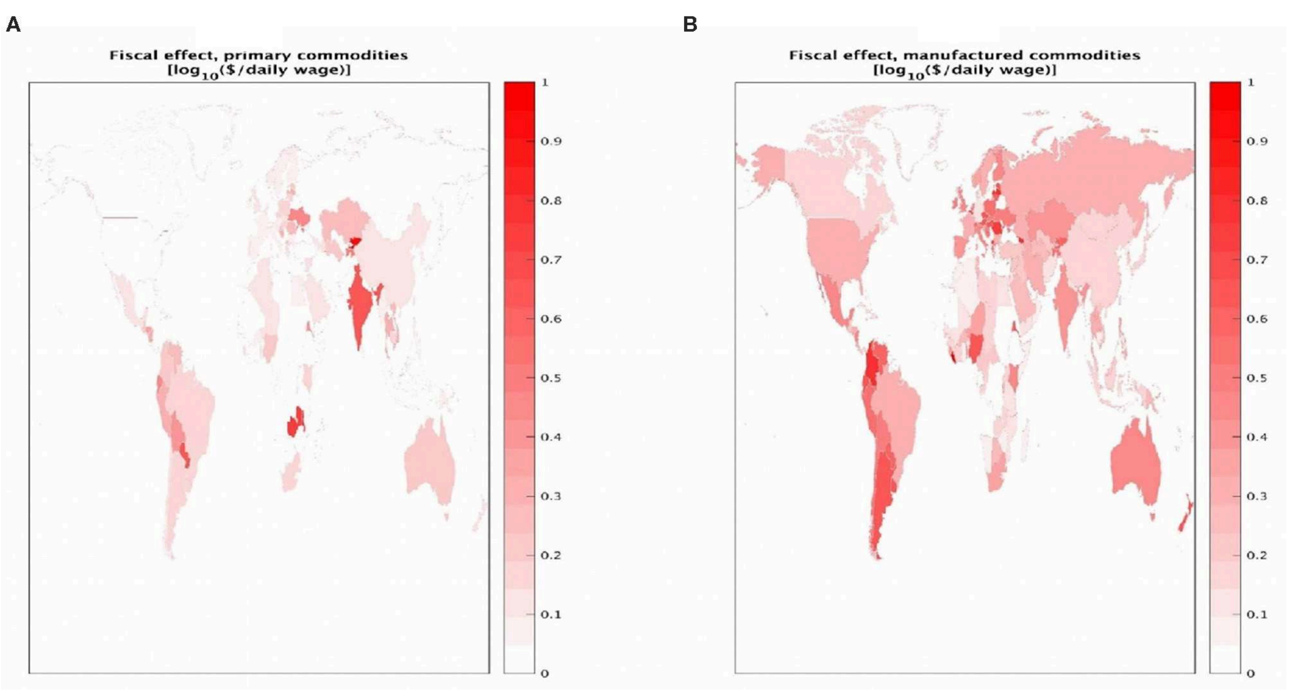


FIGURE 5 | Incidence of a 10% tax on a range of food items. Incidence of a 10% tax on the total output of a set of primary **(A)** and secondary food **(B)** items. To refer fiscal effects to a meaningful unit reflecting countries' relative wealth, color shadings reflect multiples (1–10) of each country's total daily wage payment. Left panel: Sugar beet, sugar cane, raw sugar, refined sugar. Right panel: Refined sugar, soft drinks, chocolate, ice cream, extracts.

though cocoa (and its direct products) may not directly cause adverse health effects (**Figure 6**). A similar situation exists for nut producers around the world, since nuts are a significant component in many chocolates (**Figure 7**). This result is observed owing to the linear relationship between demand for inputs and outputs in the Leontief demand-pull model.

Australians buy mainly Australian-made chocolate, but also from many other countries around the world (United Nations Statistics Division, 2016b) (**Figure 6** left panel). This chocolate requires a range of material and non-material inputs from industries situated in the supply-chain network upstream from chocolate. Including five layers of production upstream from Australian chocolate, we find cocoa processing facilities mainly in the USA, Ecuador, Brazil, the UK, Côte d'Ivoire, Ghana, Nigeria, Cameroon, South Africa, China, Thailand, Malaysia and Indonesia (center). Following the supply-chain network through to its origins with primary producers of cocoa leaves just seven main global cocoa producers: Ecuador, Côte d'Ivoire, Ghana, Nigeria, Cameroon, Malaysia and Indonesia (right). In these countries, cocoa production for the ultimate chocolate destination Australia alone is worth hundreds of mean annual incomes. Should Australian chocolate consumption decrease, these jobs would be at risk. Some types of Australian chocolate embody nuts, and these originate from Turkey (hazelnuts and walnuts), India and Vietnam, Nigeria and Côte d'Ivoire (cashew nuts), Iran (almonds) and Ukraine (walnuts) (**Figure 7**).

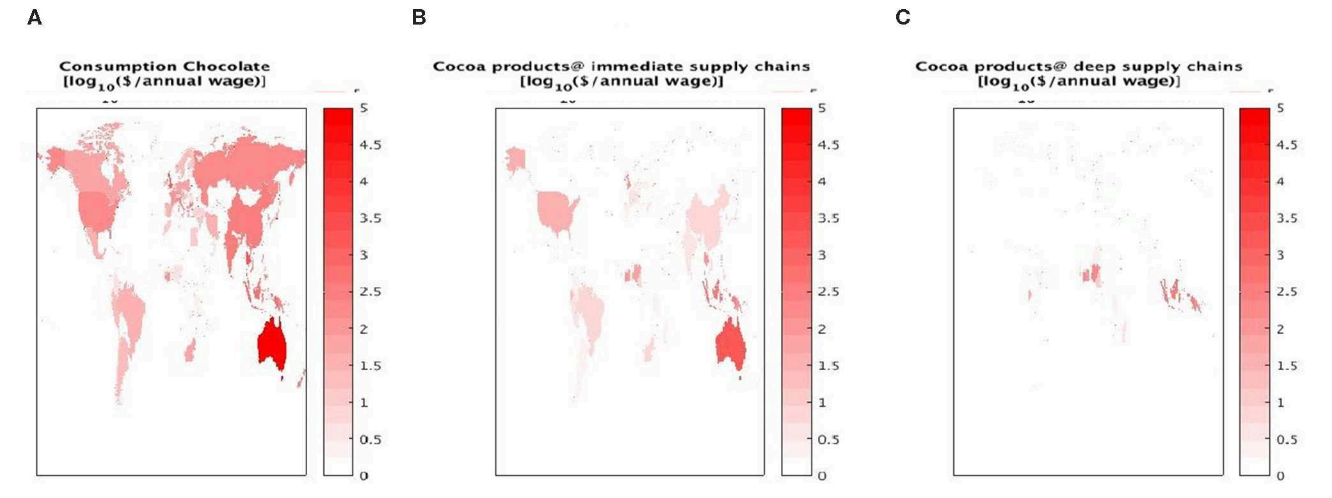


FIGURE 6 | Chocolate consumption and outputs of cocoa products. Consumption of chocolate in Australia **(A)**, and output of cocoa products in the first five supply-chain layers upstream from chocolate **(B)**, and in the remaining upstream supply chains **(C)**.

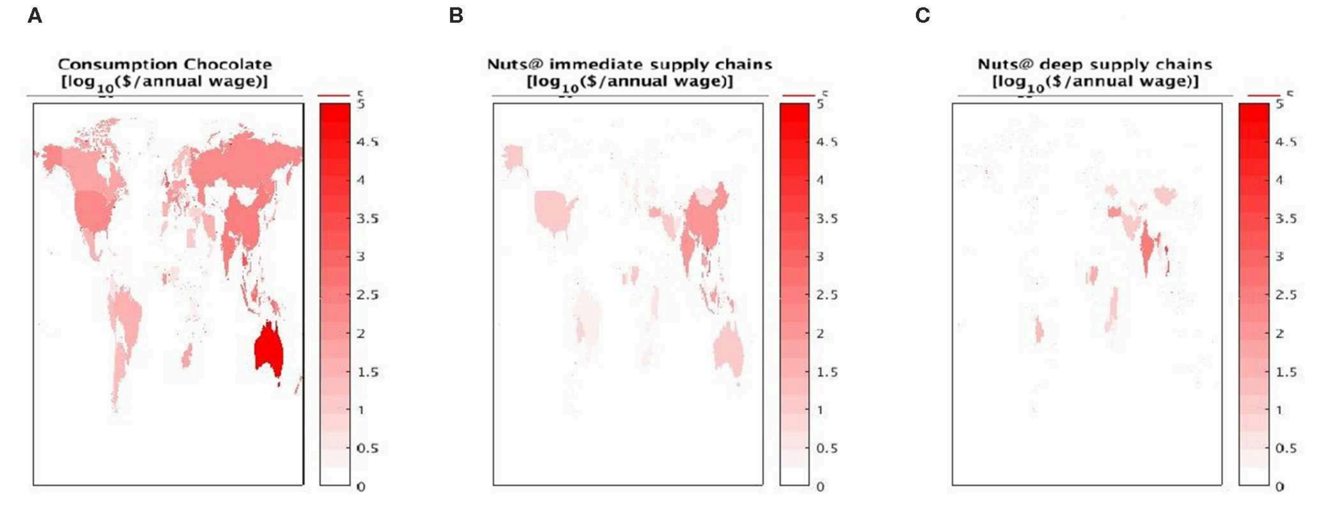


FIGURE 7 | Chocolate consumption and output of nuts. Consumption of chocolate in Australia **(A)**, and output of nuts in the first 5 supply-chain layers upstream from chocolate **(B)**, and in the remaining upstream supply chains **(C)**.

Trade, Inequality, and Food Insecurity

Food security requires constant access to sufficient, safe, nutritious food to maintain a healthy and active life (Food Agriculture Organisation, 1996). Food insecurity, a notable indicator of food inequality, can manifest itself in a number of ways. Here, we discuss two of these- hunger and obesity. In the context of food security and planetary health, the issue of hunger and food inequality warrants special investigation. The International Food Policy Research Institute (IFPRI) regularly calculates the Global Hunger Index (GHI), using well-established procedures for 118 countries, for four key component indicators: undernourishment, child-wasting, -stunting and -mortality. The comprehensive data are available for a continuous time-series from 2011 to 2016, and for separate years—1992, 2000 and 2008 (International Food Policy Research Institute, 2017). Food shortage resulting from natural disasters, such as droughts and floods, is one of the causes of hunger worldwide. The contribution of international trade in promoting or eradicating hunger is unclear (Pritchard, 2012). It has been suggested that international trade opens avenues for low- and middle-income countries to have access to large global markets allowing them to specialize in production and exploit economies of scale. There is, however, another school of thought that challenges this argument on the basis of unfair trading rules that are biased against low- and middle-income countries (Food and Agriculture Organisation, 2017; Oxfam, 2017). A potential integration of GHI with a global MRIO database, coupled with additional data for harmonizing the GHI dataset with the trade model, could yield useful insights into the implications of international trade on hunger in low- and middle-income countries. It is important to note that whilst for environmental indicators such as carbon emissions and energy use, we can enumerate the amount of emissions embodied in the consumption of a particular good or service, such a link is not clear-cut for social indicators such as a hunger or food inequality (mentioned below). These intrinsically complex issues require exploration of potential indicators that could be coupled with the global database for undertaking a supply-chain assessment.

Thinking along the lines of the income equality (Alsamawi et al., 2014b), a term used to describe inequality in accessible food is called "food inequity." It essentially means that wealthy people are eating better than ever whilst the poor are eating worse. Whilst inequity in the availability of food is primarily an issue in low- and middle-income countries, certain income groups in developed nations such as Australia face this issue as well (Australian Institute of Family Studies, 2011). The statistics on global food inequity are alarming. The Global Food security index provides information on countries that are most and least vulnerable to food insecurity. The data-set is for 113 countries, developed using a unique set of 28 qualitative and quantitative indicators (Economist Intelligence Unit, 2017). An investigation of the role of international trade as an accelerator or retardant of food inequity could yield useful insights.

At the other end of the malnourishment spectrum lies obesity. This condition, which increasingly occurs across the socioeconomic spectrum, has almost tripled in incidence since 1975 and is now considered a global epidemic (World Health Organisation, 2003, 2017a). Undernutrition and obesity may co-exist not just in the same country, region or community, but also within the same household (World Health Organisation, 2018). Recent research indicates that there may be a causal relationship between opening up trade and increasing likelihood of obesity, via increasing imports of unhealthy foods (McNamara, 2015; Barlow et al., 2017; Guintella et al., 2017; Mendez Lopez et al., 2017). Whilst IOA cannot directly work with obesity rates (since these are a characteristic of a population and not of an industrial supply-chain system), it can utilize proxy indicators of obesity, such as amounts of sugar and fat embodied in diets. Thus, combining obesity rates from the WHO Global Health Observatory Data (World Health Organisation, 2017b) with results from a trade-linked global model could reveal a potential role of globalization in the obesity problem.

CONCLUSIONS

This paper highlights the value of IOA in not only providing data to monitor against existing indicators but in developing new and more comprehensive indicators through its ability to consider whole food systems and consideration of regional and cultural circumstances. Using examples, we have illustrated the power of IOA in providing policy makers with information regarding the global impacts of policies to promote healthy and sustainable systems, so that they can mitigate these impacts through complementary policy intervention.

DATA AVAILABILITY STATEMENT

The data used in this study was taken from publicly available data sets, which are summarized in this paper.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

This work was financially supported by the Australian Research Council (ARC) through its Projects DP0985522, DP130101293, DP190102277, and LE160100066 and the National eResearch Collaboration Tools and Resources project (NeCTAR) through its Industrial Ecology Virtual Laboratory infrastructure VL 201, as well as by the Sydney Food and Nutrition Network at the University of Sydney.

ACKNOWLEDGMENTS

We would like to thank Sebastian Juraszek for expertly managing the Global IELab's advanced computation requirements, and Charlotte Jarabak for help with collecting data.

REFERENCES

Alsamawi, A., Murray, J., and Lenzen, M. (2014a). The employment footprints of nations: uncovering master-servant relationships. *J. Industr. Ecol.* 18, 59–70. doi: 10.1111/jiec.12104

Alsamawi, A., Murray, J., and Lenzen, M. (2017). Trade in occupational safety and health: tracing the embodied human and economic harm in labour along the global supply chain. *J. Clean. Prod.* 147, 187–196. doi: 10.1016/j.jclepro.2016.12.110

Alsamawi, A., Murray, J., Lenzen, M., Kanemoto, K., and Moran, D. (2014b). A novel approach to quantitative accounting of income inequality. *PLoS ONE* 9:e110881. doi: 10.1371/journal.pone.0110881

Ash, J., and Newth, D. (2007). Optimising networks for resilience against cascading failure. *Phys. Statist. Mech. Appl.* 380, 673–683. doi: 10.1016/j.physa.2006.12.058

Australian Bureau of Statistics (2016a). *Australian System of National Accounts: Concepts, Sources and Methods, 2015. ABS Catalogue No. 5216.0.* Available online at: http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/5216.02013?OpenDocument

Australian Bureau of Statistics (2016b). *Australian National Accounts: Input-Output Tables, 2013-14. ABS Catalogue No. 5209.0.* Australian Bureau of Statistics. Available online at: https://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/5209.0.55.001Main+Features12013-14?OpenDocument (accessed July 19, 2018)

Australian Institute of Family Studies (2011). *Food insecurity in Australia: What Is It, Who Experiences It and How Can Child and Family Services Support Families Experiencing It? Food Insecurity in Australia: What Is It, Who Experiences It and How Can Child and Family Services Support Families Experiencing It?* Australian Institute of Family Studies. Available online at: https://aifs.gov.au/cfca/publications/food-insecurity-australia-what-it-who-experiences-it-and-how-can-child

Barlow, P., McKee, M., Basu, S., and Stuckler, D. (2017). The health impact of trade and investment agreements: a quantitative systematic review and network co-citation analysis. *Global. Health.* 13:13. doi: 10.1186/s12992-017-0240-x

Bartelmus, P., Stahmer, C., and van Tongeren, J. (1991). Integrated environmental and economic accounting: framework for a SNA satellite system. *Rev. Income Wealth.* 37, 111–148. doi: 10.1111/j.1475-4991.1991.tb00350.x

Behrens, P., Kiefte-de Jong, J. C., Bosker, T., Rodrigues, J. F. D., de Koning, A., and Tukker, A. (2017). Evaluating the environmental impacts of dietary recommendations. *Proc. Natl. Acad. Sci. U.S.A.* 114, 13412–13417. doi: 10.1073/pnas.1711889114

Berry, E. M., Dernini, S., Burlingame, B., Meybeck, A., and Conforti, P. (2015). Food security and sustainability: can one exist without the other? *Public Health Nutr.* 18, 2293–2302. doi: 10.1017/S136898001500021X

Bíró, A. (2015). Did the junk food tax make the Hungarians eat healthier? *Food Policy.* 54, 107–115. doi: 10.1016/j.foodpol.2015.05.003

Bonnet, C., and Réquillart, V. (2013). Tax incidence with strategic firms in the soft drink market. *J. Public Econ.* 106, 77–88. doi: 10.1016/j.jpubeco.2013.06.010

Burch, D., and Pritchard, B. (1996). *The Uneasy Transition to Globalization: Restructuring of the Australian Tomato Processing Industry*. Aldershot: Ashgate Publishing Limited.

Candy, S., Biggs, C., Larsen, K., and Turner, G. (2015). Modelling food system resilience: a scenario-based simulation modelling approach to explore future shocks and adaptations in the Australian food system. *J. Environ. Studies Sci.* 5, 712–731. doi: 10.1007/s13412-015-0338-5

Capon, A., and Dannenberg, A. (2016). "Healthy communities," in *Environmental Health: From Global to Local,* ed H. Frumkin (San Francisco: Jossey Bass), 377–413.

Chaudhary, A., Gustafson, D., and Mathys, A. (2018). Multi-indicator sustainablity assessment of global food systems. *Nat. Commun.* 9:848. doi: 10.1038/s41467-018-03308-7

Chen, Z., Rose, A. Z., Prager, F., and Chatterjee, S. (2017). Economic consequences of aviation system disruptions: a reduced-form computable general equilibrium analysis. *Transp. Res. Part A Policy Practice.* 95, 207–226. doi: 10.1016/j.tra.2016.09.027

Clancy, K. (2017). Transdisciplinary and systems approaches to food security. *J. Agricul. Food Systems Comm. Dev.* 7, 13–16. doi: 10.5304/jafscd.2017.074.012

Cox, A., Prager, F., and Rose, A. (2011). Transportation security and the role of resilience: a foundation for operational metrics. *Trans. Policy.* 18, 307–317. doi: 10.1016/j.tranpol.2010.09.004

de Bruyn, J., Ferguson, E., Allmann-Farinelli, M., Darnton-Hill, I., Maulaga, W., Msuya, J., et al. (2016). Food Composition Tables in resource-poor settings: exploring current limitations and opportunities, with a focus on animal-source foods in sub-Saharan Africa. *Br. J. Nutr.* 16, 1709–1719. doi: 10.1017/S0007114516003706

Economist Intelligence Unit (2017). *The Global Food Security Index. Economist Intelligence Unit.* Available online at: https://foodsecurityindex.eiu.com (accessed 18 July, 2018)

Edjabou, L. D., and Smed, S. (2013). The effect of using consumption taxes on foods to promote climate friendly diets – The case of Denmark. *Food Policy.* 39, 84–96. doi: 10.1016/j.foodpol.2012.12.004

Eurostat (2016). *ESVG Aufkommens-, Verwendungs- und Input-Output Tabellen.* Available online at: http://ec.europa.eu/eurostat/de/web/esa-supply-use-input-tables/data/workbooks

Finley, J., Dimick, D., Marshall, E., Nelson, G., Mein, J., and Gustafson, D. (2017). Nutritional sustainability: aligning priorities in nutrition and public health with agricultural production. *Adv. Nutr.* 8, 780–788. doi: 10.3945/an.116.013995

Food and Agriculture Organisation (1996). *Rome Declaration on World Food Security and World Food Summit Plan of Action. World Food Summit 13-17 November 1996. Rome.* Food and Agriculture Organisation. Available online at: http://www.fao.org/docrep/003/w3613e/w3613e00.HTM

Food and Agriculture Organisation (2009). *Draft Declaration of the World Summit on Food Security.* Food and Agriculture Organisation. Available online at: http://www.fao.org/fileadmin/templates/wsfs/Summit/Docs/Declaration/WSFS09_Draft_Declaration.pdf

Food and Agriculture Organisation (2013). *Resilient Livelihoods – Disaster Risk Reduction for Food and Nutrition Security.* Food and Agriculture Organisation. Available online at: http://www.fao.org/3/a-i3270e.pdf

Food and Agriculture Organisation (2017). *Trade and Food Security: The Importance of Agriculture and Agricultural Trade in Developing Countries.* Available online at: http://www.fao.org/docrep/006/j0083e/j0083e04.htm (accessed July 23, 2018)

Food and Agriculture Organisation (2018). *Sustainable Food Systems: Concept and Framework.* Food and Agriculture Organisation. Available online at: http://www.fao.org/3/ca2079en/CA2079EN.pdf

Food and Agriculture Organisation, Bioversity International (2010). *Sustainable Diets and Biodiversity: Directions and Solutions for Policy, Research and Action.* Food and Agriculture Organisation and Bioversity International. Available online at: http://www.fao.org/docrep/016/i3004e/i3004e00.htm

Francis, C. A., Lieblein, T. A., Breland, L., Salomonsson, U., Sriskandarajah, G. N., and Langer, V. (2008). Transdisciplinary research for a sustainable agricultre and food sector. *Agron. J.* 100, 771–776. doi: 10.2134/agronj2007.0073

Friel, S., Dangour, A. D., Garnett, T., Lock, K., Chalabi, Z., Roberts, A., et al. (2009). Public heatlh benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *Lancet.* 374, 2016–2025. doi: 10.1016/S0140-6736(09)61753-0

Gill, T. (2006). Epidemiology and health impact of obesity: an Asia Pacific perspective. *Asia Pac. J. Clin. Nutr.* 15, 3–14. Available online at: https://www.cpc.unc.edu/projects/china/publications/1263

Gómez-Paredes, J., Alsamawi, A., Yamasue, E., Okumura, H., Ishihara, K. N., Geschke, A., et al. (2016). Consuming childhoods: an assessment of child labor's role in indian production and global consumption. *J. Industr. Ecol.* 20, 611–622. doi: 10.1111/jiec.12464

Guerrero-López, C., Molina, M., and Colchero, M. (2017). Employment changes associated with the introduction of taxes on sugar-sweetened beverages and nonessential energy-dense food in Mexico. *Prev. Med.* 105, S43–S49. doi: 10.1016/j.ypmed.2017.09.001

Guintella, O., Rieger, M., and Rotunno, L. (2017). *Weight Gains From Trade in Foods: Evidence from Mexico*. Available online at: https://voxeu.org/article/weight-gains-trade-foods-evidence-mexico.

Hagenaars, L. L., Jeurissen, P. P. T., and Klazinga, N. S. (2017). The taxation of unhealthy energy-dense foods (EDFs) and sugar-sweetened beverages (SSBs): an overview of patterns observed in the policy content and policy context of 13 case studies. *Health Policy.* 121, 887–894. doi: 10.1016/j.healthpol.2017.06.011

Harding, M., and Lovenheim, M. (2017). The effect of prices on nutrition: comparing the impact of product- and nutrient-specific taxes. *J. Health Econ.* 53, 53–71. doi: 10.1016/j.jhealeco.2017.02.003

Härkänen, T., Kotakorpi, K., Pietinen, P., Pirttil,ä, J., Reinivuo, H., and Suoniemi, I. (2014). The welfare effects of health-based food tax policy. *Food Policy.* 49, 196–206. doi: 10.1016/j.foodpol.2014.07.001

Hirst, E. (1974). Food-Related Energy Requirements. *Science.* 184, 134–138. doi: 10.1126/science.184.4133.134

Holloway, L., Kneafsey, M., Venn, L., Cox, R., Dowler, E., and Tuomainen, H. (2007). Possible food economies: a methodological framework for exploring food production–consumption relationships. *Sociol. Ruralis.* 47, 1–19. doi: 10.1111/j.1467-9523.2007.00427.x

Institute of Developing Economies-Japan External Trade Organisation (2015). *Asian International Input-Output Table.* Available online at: http://www.ide.go.jp/Japanese/Publish/Books/Tokei/pdf/2005ASIA%20TechnicalNotes.pdf

International Food Policy Research Institute (2015). *Social Accounting Matrices and Multiplier Analysis.* Available online at: http://www.ifpri.org/publication/social-accounting-matrices-and-multiplier-analysis

International Food Policy Research Institute (2017). *2017 Global Hunger Index Data. International Food Policy Research Institute.* Available online at: http://www.ifpri.org/publication/2017-global-hunger-index-data (accessed July 18, 2018)

James, D. E., and Musgrove, K. J. (1986). Integration of an economic input-output model and a linear programming technological model for energy systems analysis. *Energy Economics.* 99–112. doi: 10.1016/0140-9883(86)90034-4

James, S., and Friel, S. (2015). An integrated approach to identifying and characterising reslient urban food systems to promote population health in a changing climate. *Public Health Nutr.* 18, 2498–2508. doi: 10.1017/S1368980015000610

Kanemoto, K., Moran, D., Lenzen, M., and Geschke, A. (2014). International trade undermines national emission reduction targets: new evidence from air pollution. *Global Environ. Change.* 24, 52–59. doi: 10.1016/j.gloenvcha.2013.09.008

Kneafsey, M., Cox, R., Holloway, L., Dowler, E., Venn, L., and Tuomainen, H. (2008). *Reconnecting Consumers, Producers and Food: Exploring Alternatives.* Oxford: Berg Publishers. doi: 10.5040/9781350047631

Koch, A., McBratney, A., Adams, M., Field, D., Hill, R., Crawford, J., et al. (2013). Soil security: solving the global soil crisis. *Global Policy.* 4, 434–441. doi: 10.1111/1758-5899.12096

Kondo, Y., and Nakamura, S. (2005). Waste Input-Output Linear Programming model with its application to eco-efficiency analysis. *Econ. Syst. Res.* 17, 393–408. doi: 10.1080/09535310500283526

Kramer, K. J., Moll, H. C., Nonhebel, S., and Wilting, H. C. (1999). Greenhouse gas emissions related to Dutch food consumption. *Energy Policy.* 27, 203–216. doi: 10.1016/S0301-4215(99)00014-2

Kytzia, S., Faist, M., and Baccini, P. (2004). Economically extended—MFA: a material flow approach for a better understanding of food production chain. *J. Clean. Prod.* 12, 877–889. doi: 10.1016/j.jclepro.2004.02.004

Lal, R., Blum, W. E., Valentin, C., and Stewart, B. A. (1997). *Methods for Assessment of Soil Degradation.* Boca Raton, FL: CRC Press.

Lan, J., Malik, A., Lenzen, M., McBain, D., and Kanemoto, K. (2016). A structural decomposition analysis of global energy footprints. *Appl. Energy.* 163, 436–451. doi: 10.1016/j.apenergy.2015.10.178

Lenzen, M., Geschke, A., Abd Rahman, M. D., Xiao, Y., Fry, J., Reyes, R., et al. (2017). The Global MRIO Lab - charting the world economy. *Economic Syst. Res.* 29, 158–186. doi: 10.1080/09535314.2017.1301887

Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., et al. (2013). International trade of scarce water. *Ecol. Econ.* 94, 78–85. doi: 10.1016/j.ecolecon.2013.06.018

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., and Geschke, A. (2012). International trade drives biodiversity threats in developing nations. *Nature.* 486, 109–112. doi: 10.1038/nature11145

Lenzen, M., Murray, S. A., Korte, B., and Dey, C. J. (2003). Environmental impact assessment including indirect effects - a case study using input-output analysis. *Environ. Impact Assess. Rev* 23, 263–282. doi: 10.1016/S0195-9255(02)00104-X

Lenzen, M., and Peters, G. (2010). How city dwellers affect their resource hinterland – a spatial impact study of Australian households. *J. Industrial Ecol.* 14, 73–90. doi: 10.1111/j.1530-9290.2009.00190.x

Leontief, W. (1936). Quantitative input and output relations in the economic system of the United States. *Rev. Econ. Stat.* 18, 105–125. doi: 10.2307/1927837

Leontief, W. (1966). *Input-Output Economics.* New York, NY: Oxford University Press.

Leontief, W., and Ford, D. (1970). Environmental repercussions and the economic structure: an input-output approach. *Rev. Econ. Stat.* 52, 262–271. doi: 10.2307/1926294

Lin, C. (2011). Identifying lowest-emission choices and environmental Pareto frontiers for wastewater treatment: wastewater treatment input-output model based linear programming. *J. Industr. Ecol.* 15, 367–380. doi: 10.1111/j.1530-9290.2011.00339.x

MacMahon, A., Smith, K., and Lawrence, G. (2015). Connecting resilience, food security and climate change: lessons from flooding in Queensland, Australia. *J. Environ. Studies Sci.* 5, 378–391. doi: 10.1007/s13412-015-0278-0

Malik, A., Lan, J., and Lenzen, M. (2016). Trends in global greenhouse gas emissions from 1990 to 2010. *Environ. Sci. Technol.* 50, 4722–4730. doi: 10.1021/acs.est.5b06162

Maye, D., Holloway, L., and Kneafsey, M. (2007). *Alternative Food Geographies.* Bingley: Emerald Group Publishing Limited.

McBratney, A. B., Morgan, C. L., and Jarrett, L. E. (2017a). *The Value of Soil's Contributions to Ecosystem Services Global Soil Security.* Geneva: Springer. 227–235. doi: 10.1007/978-3-319-43394-3_20

McBratney, A. B., Santos, M. M., and Minasny, B. (2003). On digital soil mapping. *Geoderma* 117, 3–52. doi: 10.1016/S0016-7061(03)00223-4

McBratney, A. B., Field, D. J., Morgan, C. L., and Jarrett, L. E. (2017b). *Soil Security: A Rationale Global Soil Security.* Geneva: Springer. p. 3-14. doi: 10.1007/978-3-319-43394-3_1

McNamara, C. (2015). Trade liberalization, social policies and health: an empirical case study. *Global. Health* 11, 1–10. doi: 10.1186/s12992-015-0126-8

Mendez Lopez, A., Loopstra, R., McKee, M., and Stuckler, D. (2017). Is trade liberalisation a vector for the spread of sugar-sweetened beverages? A cross-national longitudinal analysis of 44 low- and middle-income countries. *Soc. Sci. Med.* 172, 21–27. doi: 10.1016/j.socscimed.2016.11.001

Mendez, V. E., Bacon, C. M., and Cohen, R. (2013). Agroecology as a transdisciplinary, participatory and action-oriented approach. *Agroecol. Sust. Food Syst.* 37, 3–18. doi: 10.1080/10440046.2012.736926

Moran, D. D., Lenzen, M., Kanemoto, K., and Geschke, A. (2013). Does ecologically unequal exchange occur? *Ecol. Econ.* 89, 177–186. doi: 10.1016/j.ecolecon.2013.02.013

Muller, F. (1973). An operational mathematical programming model for the planning of economic activities in relation to the environment. *Socio-Econ. Planning Sci.* 7, 123–138. doi: 10.1016/0038-0121(73)90051-7

NeCTAR (2013). *The Industrial Ecology Virtual Laboratory.* Available online at: https://nectar.org.au/?portfolio=industrial-ecology

Nomaguchi, T., Cunich, M., Zapata-Diomedi, B., and Veerman, J. L. (2017). The impact on productivity of a hypothetical tax on sugar-sweetened beverages. *Health Policy.* 121, 715–725. doi: 10.1016/j.healthpol.2017.04.001

Oita, A., Malik, A., Kanemoto, K., Geschke, A., Nishijima, S., and Lenzen, M. (2016). Substantial nitrogen pollution embedded in international trade. *Nat. Geosci.* 9, 111–115. doi: 10.1038/ngeo2635

Organisation for Economic Co-operation and Development (2015). *OECD Inter-Country Input-Output (ICIO) Tables.* Available online at: http://www.oecd.org/trade/input-outputtables.htm

Oxfam (2017). *What Rules and Policies Cause Hunger?* Oxfam.

Piesse, J., and Thirtle, C. (2009). Three bubbles and a panic: An explanatory review of recent food price commodity events. *Food Policy.* 34, 119–129. doi: 10.1016/j.foodpol.2009.01.001

Powell, L., Wada, R., Persky, J., and Chaloupka, F. (2014). Employment impact of sugar-sweetened beverage taxes. *Am. J. Public Health 2014.* 104, 672–677. doi: 10.2105/AJPH.2013.301630

Pritchard, B. (2012). *Trading Into Hunger? Trading Out of Hunger? International Food Trade and the Debate on Food Security. Food System Failure: The Global Food Crisis and the Future of Agriculture.* London: Earthscan.

Ridoutt, B., Hendrie, G., and Noakes, M. (2017). Dietary strategies to reduce environmental impact: a critical review of the evidence base. *Adv. Nutr.* 8, 933–946. doi: 10.3945/an.117.016691

Rose, A. (2007). Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions. *Environmental Hazards.* 7, 383–398. doi: 10.1016/j.envhaz.2007.10.001

Rose, A. (2011). Resilience and sustainability in the face of disasters. *Environ. Innovat. Soc. Trans.* 1, 96–100. doi: 10.1016/j.eist.2011.04.003

Rose, A. (2017). *Defining and Measuring Economic Resilience From a Societal, Environmental and Security Perspective*. Singapore: Springer. doi: 10.1007/978-981-10-1533-5

Rose, A., and Krausmann, E. (2013). An economic framework for the development of a resilience index for business recovery. *Int. J. Disaster Risk Reduct.* 5, 73–83. doi: 10.1016/j.ijdrr.2013.08.003

Rose, A., and Miernyk, W. (1989). Input-output analysis: the first fifty years. *Econ. Syst. Res.* 1, 229–271. doi: 10.1080/09535318900000016

SourceOECD (2009). *ITCS International Trade by Commodities Statistics.* Available online at: https://www.oecd-ilibrary.org/trade/international-trade-by-commodity-statistics_22195076

Stockholm Reslience Centre (2018). *The Nine Planetary Boundaries.* Available online at: http://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html

Suh, S. (2009). *Handbook of Input-Output Economics in Industrial Ecology*, 1st ed. Netherlands: Springer. doi: 10.1007/978-1-4020-5737-3

Suh, S., and Nakamura, S. (2007). Five years in the area of input-output and Hybrid, LCA. *Int. J. Life Cycle Assess.* 12, 351–352. doi: 10.1065/lca2007.08.358

Tamiz, M., Jones, D., and Romero, C. (1998). Goal programming for decision making: an overview of the current state-of-the-art. *Eur. J. Oper. Res.* 111, 569–581. doi: 10.1016/S0377-2217(97)00317-2

Tendall, D. M., Joerin, J., Kopainsky, B., Edwards, P., Shreck, A., Le, Q. B., et al. (2015). Food system resilience: defining the concept. *Global Food Secur.* 6, 17–23. doi: 10.1016/j.gfs.2015.08.001

The Lancet Diabetes and Endocrinology (2017). Sweet success: will sugar taxes improve health? *Lancet Diabetes Endocrinol.* 5:235. doi: 10.1016/S2213-8587(17)30070-0

The Lancet Public Health (2017). Obesity: the sweet revenge of tax. *The Lancet Public Health.* 2:e1. doi: 10.1016/S2468-2667(16)30041-X

Thow, A. M., Downs, S. M., Mayes, C., Trevena, H., Waqanivalu, T., and J. (2018). Fiscal policy to improve diets and prevent noncommunicable diseases: from recommendations to action. *Bull. World Health Organ.* 96, 201–210. doi: 10.2471/BLT.17.195982

Timmer, M. P., Erumban, A. A., Los, B., Stehrer, R., and de Vries, G. J. (2014). Slicing up global value chains. *J. Econ. Persp.* 28, 99–118. doi: 10.1257/jep.28.2.99

Tukker, A., and Dietzenbacher, E. (2013). Global multiregional input-output frameworks: an introduction and outlook. *Econ. Syst. Res.* 25, 1–19. doi: 10.1080/09535314.2012.761179

Tuomisto, H. L. (2019). The complexity of sustainable diets. *Nat. Ecol. Evol.* 3, 720–721. doi: 10.1038/s41559-019-0875-5

United Nations (1999). *Handbook of Input-Output Table Compilation and Analysis*. United Nations, editor. New York, NY: United Nations.

United Nations (2009). *European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development,* World Bank. *System of National Accounts 2008.* Available online at: https://unstats.un.org/unsd/nationalaccount/sna2008.asp

United Nations (2015). *Transforming Our World: The 2030 Agenda For Sustainable Development, A/RES/70/1.* United Nations. Available online at: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

United Nations Development Programme (2018). *Sustainable Development Goals.* Available online at: http://www.undp.org/content/undp/en/home/sustainable-development-goals.html (accessed July 17, 2018)

United Nations Environment Programme (2016). *Food Systems and Natural Resources. A Report of the Working Group on Food Systems of the International Resource Panel.* United Nations Environment Programme. Available online at: http://www.resourcepanel.org/reports/food-systems-and-natural-resources

United Nations Industrial Development Organisation (2016). *Industrial Statistics Database at the 4-Digit Level of ISIC (INDSTAT4).* Available online at: http://www.unido.org/resources/statistics/statistical-databases.html

United Nations Standing Committee on Nutrition (2017). *Sustainable Diets for Healthy People and a* ***Healthy Planet***. Available online at: https://www.unscn.org/en/unscn-publications?idnews=1739

United Nations Statistics Division (2016a). *Industrial Commodity Production Statistics Database.* Available online at: https://unstats.un.org/unsd/industry/Commodity/

United Nations Statistics Division (2016b). *National Accounts Official Data.* Available online at: http://data.un.org/Browse.aspx?d=SNA

United Nations Statistics Division (2016c). *UN comtrade - United Nations Commodity Trade Statistics Database.* Available online at: http://comtrade.un.org/

United Nations Statistics Division (2016d). *UN Service Trade Database.* Available online at: http://unstats.un.org/unsd/servicetrade/

United Nations Statistics Division (2017a). *National Accounts Main Aggregates Database.* Available online at: http://unstats.un.org/unsd/snaama/Introduction.asp

United Nations Statistics Division (2017b). *System of Environmental- Economic Accounting— SEEA Revision.* Available online at: https://unstats.un.org/unsd/envaccounting/seearev/

Venn, L., Kneafsey, M., Holloway, L., Cox, R., Dowler, E., and Tuomainen, H. (2006). Researching European 'alternative'food networks: some methodological considerations. *Area.* 38, 248–258. doi: 10.1111/j.1475-4762.2006.00694.x

Wheeler, T., and von Braun, J. (2013). Climate change impacts on global food security. *Science* 341, 508–513. doi: 10.1126/science.1239402

Wiedmann, T. (2009). Carbon footprint and input-output analysis: an introduction. *Econ. Syst. Res.* 21, 175–186. doi: 10.1080/09535310903541256

Wiedmann, T., and Lenzen, M. (2018). Environmental and social footprints of international trade. *Nat. Geosci.* 11, 314–321. doi: 10.1038/s41561-018-0113-9

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., et al. (2015). The material footprint of nations. *Proc. Natl. Acad. Sci. U.S.A.* 112, 6271–6276. doi: 10.1073/pnas.1220362110

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet.* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Wood, R., Lenzen, M., Dey, C., and Lundie, S. (2006). A comparative study of some environmental impacts of conventional and organic farming in Australia. *Agric. Syst.* 89, 324–348. doi: 10.1016/j.agsy.2005.09.007

World Bank (2017). *Global Consumption Database.* Available online at: http://datatopics.worldbank.org/consumption/

World Cancer Research Fund (2018). *WCRF International Food Policy Framework for Healthy Diets: NOURISHING.* Available online at: https://www.wcrf.org/int/policy/nourishing/our-policy-framework-promote-healthy-diets-reduce-obesity (accessed July 17, 2018)

World Health Organisation (2003). *Controlling the Obesity Epidemic*. Available online at: http://www.who.int/nutrition/topics/obesity/en/ (accessed July 18, 2018)

World Health Organisation (2017a). *Global Health Observatory Data.* Available online at: http://www.who.int/gho/ncd/risk_factors/overweight/en/ (accessed July 17, 2018)

World Health Organisation (2017b). *Overweight and Obesity*. Available online at: http://www.who.int/en/news-room/fact-sheets/detail/obesity-and-overweight (accessed July, 17 2018)

World Health Organisation (2018). *Obesity*. Available online at: http://www.afro.who.int/health-topics/obesity (accessed July 17, 2018)

World Wildlife Federation (2013). *A balance of healthy and sustainble food choices for France, Spain and Sweden.* Available online at: https://livewellforlife.eu/wp-content/uploads/2013/02/A-balance-of-healthy-and-sustainable-food-choices.pdf

Xiao, Y., Benoît-Norris, C., Lenzen, M., Norris, G., and Murray, J. (2017a). How social footprints of nations can assist in achieving the sustainable development goals. *Ecol. Econ.* 135, 55–65. doi: 10.1016/j.ecolecon.2016.12.003

Xiao, Y., Lenzen, M., Benoît-Norris, C., Norris, G. A., Murray, J., and Malik, A. (2017b). The corruption footprints of nations. *J. Industr. Ecol.* 22, 68–78. doi: 10.1111/jiec.12537

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 06 April 2021
doi: 10.3389/fsufs.2021.544072

An Approach for Integrating and Analyzing Sustainability in Food-Based Dietary Guidelines

Rachel Mazac [1,2], Kerry Renwick [3], Barbara Seed [4] and Jennifer L. Black [5]*

[1] Department of Agricultural Sciences, Faculty of Agriculture and Forestry, University of Helsinki, Helsinki, Finland, [2] Helsinki Institute of Sustainability Sciences (HELSUS), University of Helsinki, Helsinki, Finland, [3] Department of Curriculum and Pedagogy, Faculty of Education, University of British Columbia, Vancouver, BC, Canada, [4] B. Seed Consulting, Vancouver, BC, Canada, [5] Food, Nutrition and Health, Faculty of Land and Food Systems and Peter Wall Institute for Advanced Studies, University of British Columbia, Vancouver, BC, Canada

OPEN ACCESS

Edited by:
Selena Ahmed,
Montana State University,
United States

Reviewed by:
Aida Turrini,
Council for Agricultural Research and Economics, Italy
Hettie Carina Schönfeldt,
University of Pretoria, South Africa

***Correspondence:**
Rachel Mazac
rachel.mazac@helsinki.fi

Specialty section:
This article was submitted to Nutrition and Sustainable Diets, a section of the journal Frontiers in Sustainable Food Systems

Received: *19 March 2020*
Accepted: *02 March 2021*
Published: *06 April 2021*

Citation:
Mazac R, Renwick K, Seed B and Black JL (2021) An Approach for Integrating and Analyzing Sustainability in Food-Based Dietary Guidelines.
Front. Sustain. Food Syst. 5:544072.
doi: 10.3389/fsufs.2021.544072

International organizations, governments, researchers, and activists have proposed the need for deeper integration of sustainability considerations in national food-based dietary guidelines (FBDGs). Yet, as recent scholarship advances the conversation, questions remain around how to effectively frame and address the interconnectedness of multiple sustainability domains. Little systematic analysis has evaluated how current FBDGs have integrated complex messages about socially, environmentally, and economically sustainable consumption practices with nutrition and health messages. This study had two nested objectives: (i) to examine the validity of an existing sustainable diets framework by assessing how sustainability concepts have been framed and included in national FBDGs available from 2011 to 2019 and (ii) to describe a novel analysis approach that augments an existing framework which integrates sustainability domains and can be adapted for use by future FBDGs. A qualitative content analysis was used to examine sustainability concepts found in 12 FBDGs and supporting documents available in English that were developed for use in 16 countries across Europe, North and South America, and Asia as of 2019—from a global review of those published prior to 2016 and gray literature review of publications between 2016 and 2019. Health domains were the primary frame found across the FBDGs examined, but documents also commonly incorporated agricultural, sociocultural, and economic sustainability principles. Analyzed documents were used to adapt an existing policy analysis framework into a "Sustainability in FBDGs Framework." This proposed framework contributes a novel analysis approach and has five core domains that are interconnected: health and nutrition, food security and agriculture, markets and value chains, sociocultural and political, and environment and ecosystems. This study adds to the growing body of literature related to sustainable food systems and dietary guidelines by presenting how sustainability framing in FBDGs can be used to further develop a comprehensive framework for integrating sustainability domains. While this project helps to validate previous work, further analyses of FBDGs which have emerged since this study and those not available in English are needed to improve the guidance approach described here and for assessing the incorporation of sustainability domains in future FBDGs. This work is useful in informing processes for policy developers to integrate sustainability considerations into their national FBDGs.

Keywords: dietary guidelines, sustainability, sustainable diets, integrated framework, food system

INTRODUCTION

Global food systems are facing multiple sustainability challenges. Agriculture has pushed Earth's systems past planetary boundaries in biosphere integrity, biogeochemical flows, and land-system changes (Steffen et al., 2015). Sixty percent of fish stocks are completely depleted and 30 percent are over-fished (UN FAO, 2010). Estimates of 25–30% of global greenhouse gas (GHG) emissions are attributed to livestock and agricultural production (Tubiello et al., 2014). Given such challenges, global temperatures have risen and precipitation patterns have changed, perpetuating a negative feedback loop impacting food systems (Vermeulen et al., 2012).

There is recent recognition that dietary practices can improve environmental outcomes and the sustainability of the food system (Macdiarmid, 2013; Tilman and Clark, 2014; van Dooren et al., 2014; Hallström et al., 2015; Willett et al., 2019). "Environmentally-friendly" food choices and consumption patterns can have an impact on larger food systems; for example, buying direct from producers or purchasing more local foods disrupts globalized production and supply chains and can contribute to nutritious dietary practices at home (Mbow et al., 2019; Willett et al., 2019).

Calls have been made for more environmentally-sustainable diets over the last decade (Godfray et al., 2010; Foley et al., 2011; Tilman and Clark, 2014; Aleksandrowicz et al., 2016; Springmann et al., 2016; Willett et al., 2019). Plant-based diets incorporating whole grains, pulses, fruits and vegetables, and seeds and nuts, with reductions in ultra-processed and animal-based food are proposed as healthy and sustainable dietary patterns (Mbow et al., 2019; Willett et al., 2019). Still, many definitions of sustainable diets have been put forward. The existence of multiple definitions poses a challenge for developing a singular guiding recommendation for shifting dietary patterns. The study herein adopted the definition compiled by the UN FAO and Biodiversity International of healthy and sustainable diets as:

> "those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources" (UN FAO, 2018), p. 1.

Dietary guidelines have been proposed as one tool to promote sustainable dietary practices and address the complex challenge of shifting diets (Gussow and Clancy, 1986; Dye Gussow, 1999; Lang, 2017; Lang and Mason, 2017; Seed and Rocha, 2018; Willett et al., 2019). Recent evidence has shown that greater adherence to FBDGs has been correlated with more plant-based diets; further, diets following guidelines were associated with lower health costs, energy intake and environmental impact scores, more deaths averted, and less exposure to pesticides (Kesse-Guyot et al., 2020).

Abbreviations: GHG, Greenhouse gases; FBDGs, Food-based dietary guidelines; NNR, Nordic Nutrition Recommendations; SDGs, United Nations Sustainable Development Goals; UN FAO, United Nations Food and Agriculture Organization.

Food based dietary guidelines (FBDGs) are a tool to disseminate the policy guidance given by national governments, and can be the foundation of national dietary education, measurement, and monitoring activities (Seed and Rocha, 2018).

Recent political and scholarly discussions of sustainability—and its importance—in national-level nutrition policy and guidelines has grown. Members party to the Rome Declaration on Nutrition (FAO, 2014) and the United Nations (UN) Decade of Action on Nutrition (United Nations, 2017) have committed to incorporate sustainability considerations in national policy change for health and nutrition. Prior calls from scholars for sustainability in FBDGs have supported such policy transitions (Gussow and Clancy, 1986; Dye Gussow, 1999; Lang, 2017; Lang and Mason, 2017; Seed and Rocha, 2018; Willett et al., 2019).

Public health scholars and practitioners have acknowledged the need for food policy to include sustainability considerations (Sabaté et al., 2016; Wegener et al., 2018). Despite such discussions, little systematic work has evaluated how food-based guidelines integrate and frame sustainability considerations (Ahmed et al., 2019). A framework is needed for comparing progress across guidelines and as a guidance approach for future integration of multiple sustainability dimensions into FBDGs (Lang, 2017; Ahmed et al., 2019). Such a framework could be used to understand how food guides integrate sustainability considerations to meet broader international sustainability goals (Ahmed et al., 2019; Willett et al., 2019).

A shared framework for assessing and integrating sustainability into FBDGs has yet to be ratified by the larger scientific community (Lang and Mason, 2017). Studies on FBDGs where guidelines do include sustainability dimensions have found that human health aspects of sustainability (e.g., dietary diversity, limiting energy intake, plant-based foods) are more represented than socio-cultural and political, economic, and environmental aspects (Ahmed et al., 2019). Beyond health, movement toward integration of sustainability into FBDGs is limited by the lack of consensus on what constitutes and how to recommend a sustainable diet in different geographical and climatic areas and sociocultural contexts (Tuomisto, 2019; Zagmutt et al., 2019).

Framing is a form of political influence and is a theoretical and methodological tool for the study of problems and how they are discussed (Jenkin et al., 2011). Frames are important since they make some aspects of reality more salient by describing an issue, and frames offer the authors' description of the solution (Entman, 1993; Trevena et al., 2015). Framing has implications for the ways actors influence their world and make sense of issues and opinions. Given the edifying goals of FBDGs, an awareness of the way sustainability is framed is a step toward understanding how actions are being influenced toward sustainability (Trevena et al., 2015).

Some existing frameworks have been proposed as quantitative tools to inform the evaluation and modification of national food policies and dietary guidelines (Downs et al., 2017; Ahmed et al., 2019). Downs et al. (2017) developed a food policy framework and applied it to Nepalese food policy. Their framework is the first of its kind to interrogate the presence of sustainability dimensions and associated sub-dimensions in food policy. The

Downs et al. (2017) framework was developed to be applied to documents beyond Nepal. A second framework by Ahmed et al. (2019) was built upon the Downs et al. (2017). This second framework was developed specifically for examining the presence or absence of the human health, environmental, economic, as well as sociocultural and political sustainability dimensions in FBDGs (Ahmed et al., 2019). It has been noted that further use of these existing frameworks is needed to address the qualitative framing and interconnectedness of the various sustainability domains (Ahmed et al., 2019).

Frameworks intended to guide choice and policy need to acknowledge and navigate complexities of the food system (Ahmed et al., 2019; Mbow et al., 2019; Willett et al., 2019). Frameworks need a way to recognize the interconnectedness of food, health, and the environment in signaling needed environmental, policy, and system improvements. Such food system interconnections include environmental and socio-cultural dimensions (e.g., preference, food security) and do not assume consumption choices are driven solely by health (Rizvi et al., 2018).

The overall aim of this study was to examine how sustainability is framed in FBDGs. This study contributes a novel analysis approach to and validation of existing frameworks. Such adaptation applies existing frameworks to enable qualitative investigation of sustainability domains and examine complex interconnections in those domains for recommending healthy and sustainable diets. This study has two main, nested objectives. The first objective was to examine the validity of an existing sustainable diets framework by assessing how sustainability concepts have been framed and included in national FBDGs available from 2011 to 2019. This was done by focusing on: (i) how sustainability concepts were framed and included in FBDGs developed explicitly with sustainability considerations in guideline planning and writing prior to 2019; (ii) how concepts were interconnected in current FBDGs; and (iii) how the current analysis builds on recent literature regarding international sustainability framing in FBDGs. We aim to adapt existing frameworks and further apply a novel analysis approach to elicit a comprehensive framework which graphically depict the key domains, concepts, and their interconnections. The second objective uses the findings of the first objective to propose framework adaptations that graphically represent the overlaps and interconnections of diverse sustainability concepts.

MATERIALS AND METHODS

Document Collection and Inclusion Criteria

The initial selection of the FBDG documents analyzed in this study was based on the UN FAO global review of FBDGs in 2016 (Gonzalez Fischer and Garnett, 2016). The study identified 83 of the 215 countries worldwide (39 percent) as having FBDGs, of which 11 (representing 15 countries) included sustainability considerations. Though many other countries have FBDGs, the scope of this study applied only to those identified by the global UN FAO review with *explicit* sustainability considerations in planning and writing of the documents of those published prior to 2016 and our gray literature review of publications between 2016 and 2019.

The UN FAO review divided these eleven FBDGs into three categories related to the extent of integration of sustainability concepts (Gonzalez Fischer and Garnett, 2016). The first category identified four countries (Brazil, Germany, Qatar and, Sweden) that have official guidelines with explicit references to sustainability in their main messaging: "Official guidelines that include sustainability." The second category of FBDGs described four documents (the Nordic Nutrition Recommendations, United Kingdom, France and, the Netherlands FBDGs) with "Quasi-official guidance that combines health and sustainability messaging." Quasi-official guidelines were defined as "those that stem from government agencies or government funded entities" (p. 17). The final category consisted of three countries (Australia, China and, United States) with attempts to include sustainability. The meaning of attempts included those documents where "environmental considerations reach[ed] an advanced stage but [did] not achieve government endorsement" (p. 3).

National FBDG documents were sourced from the FAO database (Food Agriculture Organization of the United Nations, 2019). Documents were included in this analysis if the document was highlighted by the FAO review in one of the three above described categories. A review of the FAO database revealed no other FBDGs published after the UN FAO report with sustainability explicitly placed in their guide. However, the 2019 Canadian Dietary Guidelines document "for Health Professionals and Policymakers" was also included. The Canadian guidelines were released and added after an initial analysis because they included explicit language identifying the environmental impacts of diets as a consideration (Health Canada, 2019). Documents were excluded if not available in English (e.g., official French FBDG in French) or included no specific or explicit connection to sustainability integration. Ten official FBDGs and two supporting documents from 16 countries or regions were therefore analyzed; see document description in **Table 1**.

First Objective: Examine How Sustainability Has Been Framed in National FBDGs

This study followed the qualitative content analysis procedure from Mayring (2004) to examine the sustainability domains used in current FBDGs and how sustainability concepts are interconnected. Qualitative content analysis involves three main parts: (i) examining collected documents using content analysis categories formed from a foundational framework, (ii) building upon the framework with the data collected, and (iii) performing formative and summative checks of the content analysis categories used. To make use of the concepts and definitions in previous literature and the emergent data, this study used combinations of deductive and inductive coding in qualitative content analysis.

Within each document, line-by-line coding produced the qualitative data. Coding was completed through close reading of the documents where content was coded based on defined categories. Domains for this analysis were based on the pre-existing domains of sustainable food policy framework by the Downs et al. (2017), on which Ahmed et al.'s (2019) framework

TABLE 1 | Summary of Food-based Dietary Guidelines and related documents examined ($n = 12$), table separated by category of sustainability inclusion.

FBDG group	Country	Document	Year published	Publisher (reference)	Types of document development stakeholders
Sustainability in official FBDG	Brazil	Dietary guidelines for the Brazilian population	2015	Ministry of Health of Brazil (Ministry of Health of Brazil, 2015)	Ministry of health, Center for epidemiological research in nutrition of the university of Sáo Paulo, Brazilian Pan American health organization office, experts from health, education, social protection, and agriculture, researchers, representatives of civil society groups (professional councils, associations, public policy social control councils, consumer protection organizations)
	Germany	Ten guidelines for wholesome eating and drinking from the German nutrition society	2013	German Nutrition Society (German Nutrition Society, 2013)	German nutrition society, ministry of health, ministry of agriculture
	Qatar	Qatar dietary guidelines	2015	Qatar Ministry of Public Health (Supreme Council of Health, 2015)	National dietary guidelines taskforce, public health and nutrition representatives, Qatar national food security program, academics, medical associations, research centers, supreme council of health
	Sweden	Find your way to eat greener, not too much and to be active!	2015	Swedish National Food Agency (Swedish National Food Agency, 2015)	National food agency, public health agency, Swedish board of agriculture, food industry, research centers, public health and nutrition experts, consumer organization, patient organizations
	Canada	Canada's dietary guidelines for health professionals and policymakers	2019	Health Canada (Health Canada, 2019)	Health Canada, policy makers, public consultations, experts
Sustainability in supporting/quasi-official FBDG	France	French national nutrition program (supporting the French food guide for all - avail. in French)	2011	Ministry of Health; National Institute for Prevention and Health Education (Department of Health, 2012)	French national nutrition and health program
	The Netherlands	Dutch dietary guidelines (advisory report)	2015	Health Council of the Netherlands (Health Council of the Netherlands, 2015)	"Expert committee;" health council of the Netherlands standing committee on public health; standing committee on health care (revised and endorsed report); Netherlands nutrition centre; national institute of public health and the environment
	Denmark, Estonia, Finland, Iceland, Norway (Sweden)	Nordic nutrition recommendations - 2012	2014	Nordic Council of Ministers (Nordic Council of Ministers, 2014)	Various ministries of health in Sweden, Finland, Denmark, Norway, Iceland
	United Kingdom	United Kingdom eatwell guide booklet	2016	Public Health England (Public Health England, 2016)	Public health England, food standards Scotland, welsh government, food standards agency in Northern Ireland
Sustainability attempts in FBDG	Australia	Australian dietary guidelines	2013	National Health and Medical Research Council (National Health and Medical Research Council, 2013)	National health and medical research council; leading experts in the fields of nutrition, public health, industry, and consumer issues; commonwealth department of health
	China	Chinese dietary guidelines and the food guide pagoda	2016	Chinese Nutrition Society (Wang et al., 2016)	Chinese nutrition society; "various stakeholders;" commission of experts from the Chinese nutrition society; ministry of health
	United States of America	2015–2020 Dietary guidelines for Americans	2015	U.S. Department of Health and Human Services; U.S. Department of Agriculture FBDGs (U.S. Department of Health, Human Services, and U.S. Department of Agriculture, 2015)	U.S. department of agriculture; U.S. department of health and human services; advisory committee (prestigious researchers and scientists in the fields of nutrition, health, and medicine)

was also based. The five domains identified were: nutrition and health, food security and agriculture, environment and ecosystems, markets and value chains, and sociocultural and political. Each domain has several concepts that were used to code document references (i.e., the data collected), indicating their inclusion in each domain. Collected data were organized by domain and concepts to understand the content covered and how sustainability concepts were included. For this analysis, all 60 concepts from the original Downs et al. (2017) framework were included to determine if there was inclusion of all concepts.

This qualitative research coding approach sought to elicit core, common themes from a large body of data. This study follows the single reviewer methods of policy analysis and single knowledgeable coder approaches, reproducible if other similarly knowledgeable coders apply the same method (Campbell et al., 2013; Seed, 2015). Using such a qualitative approach did not seek to provide quantitative assessments of reliability imbued with positivistic bias (Syed and Nelson, 2015). This approach was used as it is appropriate for seeking meaning and deep understanding of the data, not seeking quantitative reliability but complex understanding. To improve quality of coding, four readings were completed of each document, with reformulating and re-coding each time. The first author carried out all reading and coding which is supported by Krippendorff's position that having multiple coders "does not affect the measured reliability" (Krippendorff, 2004) p. 219.

The initial content analysis categories were the concepts and definitions from Downs et al. (2017). Concepts were then adapted and combined based on emergent data from the documents and from Ahmed et al.'s (2019) framework. In the combined deductive-inductive approach that was utilized in the study (Drisko and Maschi, 2015), the sources of each concept and examples of the coded data are provided below. Concepts covered in the documents that did not fit within the original framework were added from the data (i.e., the FBDGs examined) in an iterative and recorded inductive process. With each addition or shifting of the concepts, a review of the previously examined documents occurred to investigate the use and connections the given concept shifts.

To investigate the interconnection of concepts in the coded data, matrix coding queries were run in QSR International's NVivo12 Software for cross-concept comparison. Text segments that were coded under two or more concepts were highlighted and reviewed for their use across documents. Review of the text under two or more concepts also included investigation of the way that each piece of text overlapped with more than one domain.

Second Objective: Adaptation of the "Sustainability in FBDGs Framework"

The framework used in this study was informed by the domains and concepts from Downs et al. (2017) as well as concepts identified in the literature evaluating sustainable diets and food policy (Ahmed et al., 2019). The 12 documents (FBDGs and supporting documents) were examined for their inclusion of sustainability concepts based on those domains. A literature review of both peer-reviewed and gray literature in addition to Downs et al. (2017) was conducted. The literature reviewed, based on Downs et al. (2017), informed the definitions and concepts included in considerations of sustainable diets such as *health influence of agriculture* (Garnett et al., 2014), *seasonal, local, and indigenous crops* (Burlingame and Dernini, 2012), *fossil fuel use* (Johnston et al., 2014), *water quality* (Behrens et al., 2017), *agricultural inputs* (Donini et al., 2016), *biodiversity* (Röös et al., 2015; Lang and Mason, 2017), and *adequate infrastructure and access to markets* (Gonzalez Fischer and Garnett, 2016).

Formative and summative framework checks—the final, iterative component of qualitative content analysis—were undertaken after the coded data from the national documents was analyzed. Checks were made for how accurate and complete the sustainability domains in the framework were as they related to food and diets. The formative framework checks guided concept fit into their respective domains and checked for relevancy through framework improvement and ongoing feedback. A summative check for validity was done after the process concluded by the first author employed a final review of all concepts and documents.

Formative feedback on the comprehensiveness of considering sustainability in FBDGs, areas of overlap of the concepts, and areas for improvement on the Downs et al. (2017) framework (i.e., where concepts were missing from their food policy context compared to FBDGs) was collected from a group of 12 food system sustainability professionals and educators. These food systems education experts were asked to review the framework in a focus group-style discussion based on their expertise as sustainable food systems practitioners after they had volunteered to participate, were made aware that this was an anonymous discussion for formative peer-review of the framework, and give verbal consent. Formative framework checks specifically asked the reviewers to consider: (i) identifying concept and sub-definition strengths and weaknesses (i.e., how accurately the description is of what defines the content of each concept) and target areas of work and, (ii) recognition of when concepts might be moved to different domains, cut, or added.

The *post hoc* summative framework check compared the adapted framework with the Ahmed et al. (2019) framework; our study addresses the call for a qualitative validation of their 2019 work. Following qualitative content analysis methodology, the domains of the framework herein were confirmed through comparison with the sustainability dimensions in the sustainability framework tool for evaluating FBDGs of Ahmed et al. (2019). See concepts confirmed by Ahmed et al. (2019) below (e.g., waste [solid, plastic, packaging], food system, and healthy weight).

RESULTS

First Objective

Inclusion of Sustainability Concepts in Documents

Table 2 presents selected examples (non-exhaustive) in each domain of text coded in multiple domains and describes the interconnectedness of each example from all 12 of the FBDGs. The five main sustainability domains, and 60 concepts defined within these domains used to guide this analysis, are described in depth in **Table S1** and encompass concepts related to diverse

TABLE 2 | Selected examples (non-exhaustive) of text coded in each domain and an indication of the other domains each example is interconnected with; color is included: blue for sociocultural and political (Sc+P), green for environment and ecosystems (E+E), red for health and nutrition (H+N), orange for food security and agriculture (FS+Ag), and purple for markets and value chains (M+VC).

Domain	Example text	Example reference	Domain(s) also coded under				
			E+E	FS+Ag	H+N	M+VC	Sc+P
Environment + ecosystems	Depending on their characteristics, the production and the distribution of foods can be socially and environmentally sustainable, promoting justice and protection of the living and physical world, or else may generate social inequalities and threats to natural resources and biodiversity.	Brazil FBDG		X		X	X
	Free-range beef and lamb can also have positive effects. In Sweden, for example, they help to produce a rich agricultural landscape and ensure that natural pastures are kept open. This benefits lots of species under threat.	Sweden FBDG		X			X
	The production and consumption of food, including processing, packaging, transportation, and waste disposal all affect our environment.	Qatar FBDG		X		X	
	Assessing and measuring the environmental impact of food choices can be complex and challenging. This is because all food production requires land, water, and energy. Further, the environmental impact of any food can vary greatly based on factors such as where the food comes from, the packaging, and how it is produced, processed, and transported.	Canada FBDG		X		X	X
	Use the Eatwell Guide to help you get a balance of healthier and more sustainable food. It shows how much of what you eat overall should come from each food group.	UK FBDG			X		
Food security + agriculture	Considering the multiple determinants of feeding practices and the complexity and challenges that are involved in the shaping of current food systems, the food guide reinforces the commitment of the ministry of health to contribute to the development of strategies for the promotion and realization of the human right to adequate food.	Brazil FBDG					X
	There are many different ways that these nutrient-dense foods can be chosen to contribute to nutritious dietary patterns that suit personal preferences. However, economic, social and cultural factors can affect the ability of individuals and groups to access nutritious foods.	Australia FBDG			X	X	X
	During ecological cultivation, no chemical pesticides are used, which decreases the total usage of chemicals and the spreading of these to the surrounding environment. This contributes to a poison-free environment and is positive for biological diversity, especially in large-scale agricultural landscapes. Certain aids are allowed, such as sulfur, soap water and lime. Further, weeds and pests are controlled through for example choice of type, crop succession, mechanical processing and a longer distance between plants.	Sweden supporting document	X				
	Food systems of indigenous peoples include the food plant and animal species that indigenous peoples acquire from land, water, and air using technologies and knowledge that have been adapted and passed through generations. This knowledge is key for sustainable harvesting and cultivation, as well as the preparation, storage, consumption and sharing of traditional food.	Canada FBDG	X				X
	Nevertheless, following the guidelines is not sufficient to significantly reduce food-related ecological burden; that would unquestionably require changes in the food production chain.	Netherlands FBDG	X		X	X	
Health + nutrition	Adequate and healthy diet should be accessible both physically and financially, and harmonious in quantity and quality, meeting the needs of variety, balance, moderation, and pleasure. Furthermore, it should derive from sustainable practices of production and distribution.	Brazil FBDG	X	X		X	X

(Continued)

TABLE 2 | Continued

Domain	Example text	Example reference	Domain(s) also coded under				
			E+E	FS+Ag	H+N	M+VC	Sc+P
	Beyond nutritional benefits, children and teens who eat together with their families are more likely to get better grades in school, have a broader vocabulary, use less substances like tobacco, be less depressed, and contribute more to their community and society.	Qatar FBDG					X
	Over the past century, deficiencies of essential nutrients have dramatically decreased, many infectious diseases have been conquered, and the majority of the U.S. population can now anticipate a long and productive life. At the same time, rates of chronic diseases—many of which are related to poor quality diet and physical inactivity—have increased.	US FBDG				X	
	For example, Indigenous Peoples who live in remote, isolated, and northern communities often have limited access to nutritious foods (including traditional food). This may be negatively influenced by limited employment opportunities and low incomes; environmental changes affecting traditional food harvesting and consumption; lack of access to the land and resources; loss of cultural identities, traditional knowledge, and food practices; and the unreliable supply, quality, and high prices of store foods in remote communities.	Canada FBDG	X	X		X	X
	Eliminate waste and develop a new ethos of diet civilization. Treasure and prepare foods according to the need for consumption. Promote separate meals for individuals to eliminate waste. Food should be fresh and hygienic, and properly handled for cooking.	China FBDG	X				X
Markets + value chains	Support and find bargains at specialty shops, municipal and farmers' markets, street vendors, and other places selling fresh or minimally processed foods, including those produced by organic and agro-ecological methods	Brazil FBDG	X	X	X		X
	There is an urgent need to nationally monitor and sustainably address the factors affecting the price of nutritious foods, particularly for vulnerable groups who suffer a disproportionate burden of poor health. In urban areas there may be less access to supermarket foods and greater access to fast foods.	Australia FBDG	X	X	X		X
	In most parts of the world, the means of production and distribution of food has been changing, in ways that jeopardize the equitable distribution of wealth, the autonomy of farmers, the generation of employment and income opportunities, and the protection of natural resources and biodiversity, as well as production of safe and healthy food.	Brazil FBDG	X	X	X		X
	All sectors—including agriculture, environment, education, housing, transportation, the food industry, trade, as well as child, family and social services—have a role to play for Canada's dietary guidelines to have far-reaching and longstanding effects on the nutritional health of Canadians.	Canada FBDG	X	X	X		X
	Food systems, including food production, food consumption, export, import, transport, storage, and retail, account for about 20–25% of all greenhouse gas emissions in European countries. Emissions of CO2 are tied to the use of fossil fuels in the production and transport of food.	Nordic Nutrition Recommendations	X	X			X
Sociocultural + political	The expansion of the production of natural or minimally processed food, particularly those originating from agro-ecological agriculture, depends on increased demand. With the increased demand for these foods, there will be a corresponding increase in the number of producers and traders, and consequently, price reductions.	Brazil FBDG		X	X	X	

(Continued)

TABLE 2 | Continued

Domain	Example text	Example reference	Domain(s) also coded under				
			E+E	FS+Ag	H+N	M+VC	Sc+P
	High fiber vegetables are an eco-friendly choice. They have less of an impact on the environment than salad greens and can be stored for longer. Ecolabelling makes it easier to find fruit and vegetables that have been grown in eco-friendly ways. Only a very small number of chemical pesticides can be used in organic farming, and climate certification is helping to reduce climate impact.	Sweden FBDG	X	X	X		
	The Qatar dietary guidelines are part of the national nutrition and physical activity action plan 2011–2016. They lay the foundation for the promotion of healthy eating and the development of healthy food policy.	Qatar FBDG			X		
	Determinants of health: the key factors that influence health, including income and social status; social support networks; education and literacy; employment and working conditions; the social and physical environments; personal health practices and coping skills; healthy child development; biology and genetic endowment; health services; gender and culture.	Canada FBDG			X		
	Improving the environment with the aim of making healthy eating choices accessible to all is a fundamental public health strategy that is an essential complement to communication, information and nutritional education campaigns.	France supporting document	X	X	X		

topics such as food literacy, fossil fuel use, diverse production systems, healthy weight, food safety, and agricultural livelihoods.

The extent to which the FBDGs addressed the different concepts of the framework varied, but no document included fewer than 11 (17%) of the concepts.

Overall, the documents most frequently framed their recommendations using concepts from the health and nutrition domain. Health and nutrition framing brought in discussions of food choices and staying physically active for maintaining a healthy weight, as well as food safety and dietary diversity as important features of a healthy diet, tied to the sociocultural domain. Some concepts and framing in the sociocultural and political domain mostly addressed food literacy (e.g., reading labels) and consumer demand (e.g., overconsumption and ready-made foods), tied to the health aspects for example. Markets and value chains were a topic covered mostly in relation to access to markets and transportation as it related to GHG emissions, which was also tied to the environment and ecosystems domain. Most recommendations that were directly related to the environment included eating less meat and processed foods and some were framed through discussion of food and packaging waste and air and water quality as they related to the environment and health. Less frequently discussed, but still present were recommendations framed around food security and agriculture, which were mostly discussed in terms of nutritious, local, and seasonal food with a few mentions of diverse production systems and soil health.

Conceptual Complexity

To illustrate the interconnectedness of sustainability concepts and their inclusion in the texts, the framework adapted in this study reformats the Downs et al. (2017) framework (see **Figure 1**). This reformatting adapted Downs et al.'s grouping of concentric circles by overlapping circles in a five-part Venn diagram that indicates a blurring of their heretofore distinct domains. This study thus presents an adpatation of the Downs' framework, in that it depicts interconnectivity through conceptual overlaps and definitions that encompass wider understanding of the concepts. Selected examples of interconnected text from each document examined are given in **Table 2**.

To visually depict the areas of frequent conceptual overlap, **Figure 1** was used to indicate which of the five domains of the framework each concept was coded under: blue for sociocultural and political, green for environment and ecosystems, red for health and nutrition, orange for food security and agriculture, and purple for markets and value chains.

To illustrate this interconnectedness, the following three quotes demonstrate the interconnected nature of the concepts that inform the framework proposed here:

> "Depending on their characteristics, the production and the distribution of foods can be socially and environmentally sustainable, promoting justice and protection of the living and physical world, or else may generate social inequalities and threats to natural resources and biodiversity" (Ministry of Health of Brazil, 2015), p. 18.

A second quote depicts the complex, interconnected use of the different domains in one main idea in this quote also from the Brazil FBDG:

> "Adequate and healthy diet should be accessible both physically and financially, and harmonious in quantity

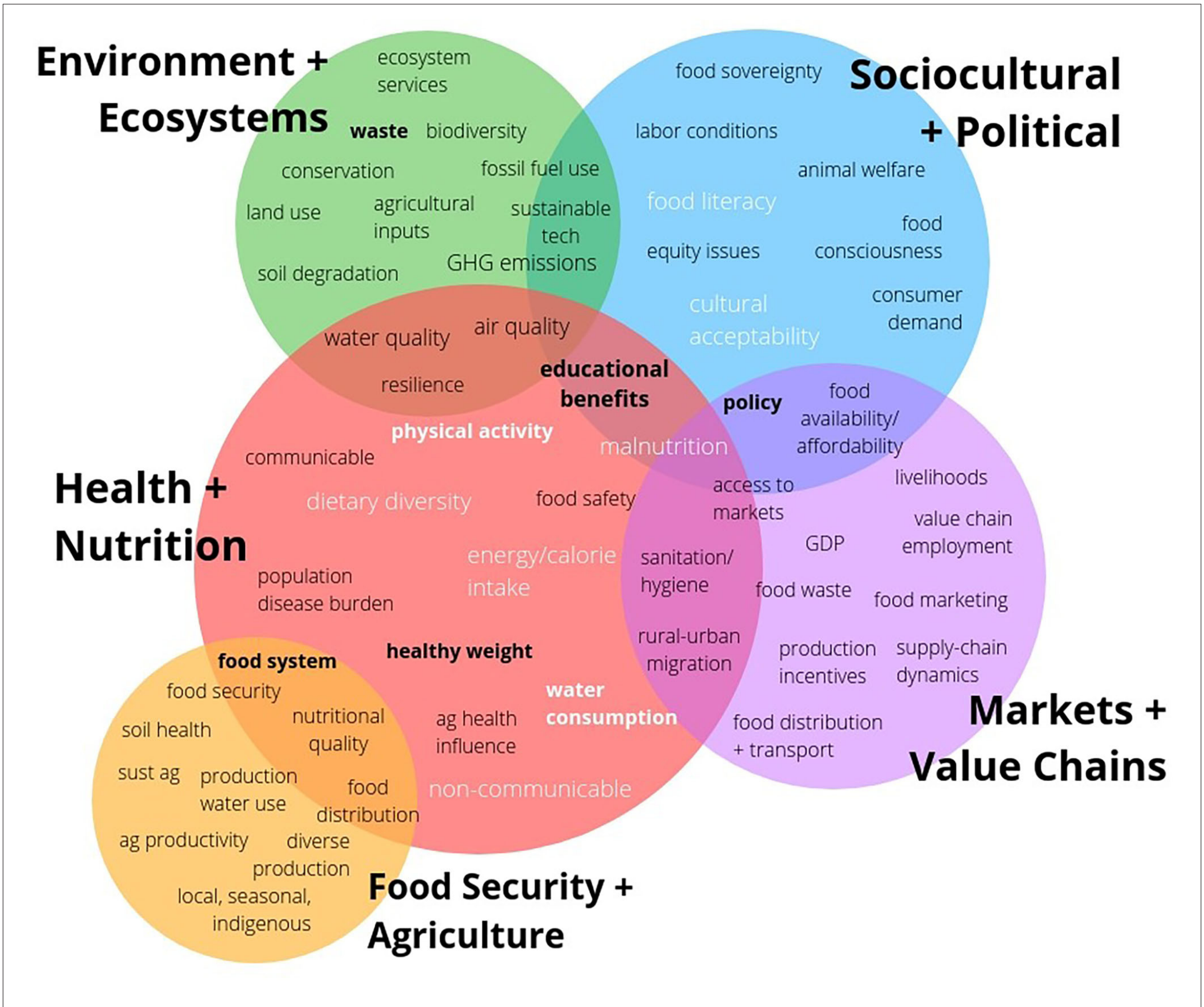


FIGURE 1 | Sustainability in Food-Based Dietary Guidelines (FBDG) Framework. Domains and concepts included in FBDGs with sustainability domains; concepts in white included in all documents reviewed ($n = 12$), concepts in bold were inductively added by the author from this analysis. GHG, Greenhouse Gases; GDP, Gross Domestic Product; ag, agriculture.

> and quality, meeting the needs of variety, balance, moderation, and pleasure. Furthermore, it should derive from sustainable practices of production and distribution" (Ministry of Health of Brazil, 2015), p. 8.

The most recently published of all documents included in this study, the Canadian Dietary Guidelines (albeit, in the background documentation "for Health Professionals and Policymakers") presents a unique and interwoven consideration of the food systems of Indigenous Peoples in Canada. The larger social determinants of health structures—especially as they pertain to Indigenous communities—are a consistent focus of their 2019 publication, which present challenges to sustainable food systems in the Canadian context:

> "Food systems of Indigenous Peoples include the food plant and animal species that Indigenous Peoples acquire from the land, water, and air using technologies and knowledge that have been adapted and passed through generations. This knowledge is key for sustainable harvesting and cultivation, as well as for the preparation, storage, consumption, and sharing of traditional food" (Health Canada, 2019), p. 36.

The circles of the framework shown in **Figure 1** are overlapping, providing an indication of the interconnectedness among the different domains represented in the food guides (see also **Table 2**). **Figure 1** shows how the different aspects of food and eating (i.e., social, environmental, economic) overlap in complex ways. Overlapping circles and size of the circles in **Figure 1** were driven by the percent overlap and number of references coded for each concept, respectively.

Second Objective: Adaptation of the "Sustainability in FBDGs Framework"

The framework was finalized into five domains and concepts within those domains. **Figure 1** represents the "Sustainability in FBDGs Framework." Eight concepts were included in all 12 of the documents reviewed (i.e., physical activity, food literacy, cultural acceptability, malnutrition, dietary diversity, energy/calorie intake, water consumption, and non-communicable diseases). These are highlighted using white text in **Figure 1**. *Post hoc* framework comparison noted that several of the same domains and concepts were also evident in Ahmed et al.'s (2019) recent work, confirming the relevance of the addition of several concepts.

While most of the concepts included in the framework for FBDGs were based on Downs et al. (2017), a further seven were added as a result of the analysis in this study—-waste, food system, educational benefits of diet, healthy weight, physical activity, water consumption, and policy. These concepts were not evident in the Nepalese food policy context, examined in Downs et al. (2017), but were identified in the 12 FBDG documents included this study and are represented as bold text in **Figure 1**.

Three concepts—stability, on-farm food loss, and land tenure—were included in the original Downs et al. (2017) framework, but none of the FBDGs reviewed in this study made any reference to them. As a result, these were not included in the final framework of this study.

DISCUSSION

Lessons Learned From Examining Sustainability in FBDGs

This study adapted a framework for integration of sustainability concepts into FBDGs based on Downs et al.'s (2017) work on food policy and further contributes to the validation of Ahmed et al.'s (2019) framework for FBDGs. Differing from Ahmed et al.'s (2019) approach, this study included FBDGs that have been identified as incorporating sustainability domains. The results of this analysis corroborate Downs and Ahmed finding that sustainability is a complex and interconnected concept and practice that is evident in recent national FBDGs (Ahmed et al., 2019). This work substantiates previous frameworks through a review of FBDGs which specifically include sustainability considerations and graphically depicts the key domains, concepts, and their interconnections for qualitative review of sustainability domains in FBDGs.

Adapting Downs et al.'s (2017) framework, this study explored how it could be possible to visually depict separate domains while also enabling inclusion of the interconnectivity of concepts in sustainability, a process which answers calls for a reapplication and development of their framework as a visual medium for further policymaking. These results represent findings building upon the Downs et al. (2017) framework and demonstrated conceptual complexity within current FBDGs. There has been a rapid introduction and evolution of sustainability considerations in FBDGs since 2011 and more recently between 2016 and 2019, evidenced in this study. Despite the limitations of their temporal boundaries, this work examines an important set of FBDGs which add insight in an era of rapid development of dietary recommendations for sustainability. This finding was also evident and confirmed in Ahmed et al.'s (2019) work. Yet, distinct from these earlier frameworks, this study elicited many examples of overlapping coding (i.e., text that was coded into more than one domain) and included FBDGs identified by the FAO as explicitly incorporating sustainability considerations, indicative of the interconnected use of the concepts within the various domains. Recognizing that different components of a sustainable diet can have greater impacts on the environment, nutrition, or agriculture than others (Downs et al., 2017; Ahmed et al., 2019), there is no current consensus about the weight of the different trade-offs inherent in improving and promoting one aspect of sustainability at the potential cost of others.

Investigating the interconnectedness of concepts was possible through the use of text coded in two or more concepts and domains and elicited five domains and 57 total concepts. Many of the concepts were found to be relevant to multiple domains, and thus depicting the possibility of making complex sustainable and healthy dietary recommendations in current national FBDGs (see examples in **Table 2**). Regardless of the length of each document, all included at least four out of five domains and often included many concepts within each domain. While some of the FBDGs were identified by the UN FAO as having the most comprehensive inclusion of sustainability, that is Australian and Brazilian (Gonzalez Fischer and Garnett, 2016), there was not complete inclusion of all sustainability concepts within any single FBDG.

Overlapping coding was found in all documents in this study and gives further evidence to the interconnected inclusion of sustainability domains. These findings demonstrate the challenges of fitting concepts into one specific area, as their relevance is largely shared across domains. The results of this study visually represent the interconnected nature of food, health, and the environment. Such results yield recommendations for users (e.g., policymakers) applying this framework to acknowledge the conceptual complexity of sustainability domains and their interconnections. Though we recognize the need for parsimony in representing the interconnected aspects of sustainability, it is important that frameworks also find ways to represent and acknowledge such complexities.

When reviewing the food guidelines it was evident that the documents were more focused on the health and nutrition domain than food security, agriculture, and environment and ecosystem domains, which was expected as these were FBDGs, not food policies (Ahmed et al., 2019). For example, six of the eight concepts included in all of the documents reviewed relate mostly to health and nutrition: physical activity, malnutrition, dietary diversity, energy/calorie intake, water consumption, and non-communicable diseases; with the others, food literacy and cultural acceptability (also included in all documents reviewed), categorized in the sociocultural and political domain. Yet, several of these concepts are also linked to other domains. For example, malnutrition is also connected to sociocultural and political structures and inequities (Ingram, 2011), and non-communicable diseases are also linked to pervasive food marketing, "fad diets," and advertisements (McGinnis et al., 2006).

Integrating the health and nutrition domain with the other four in the framework is a step toward depicting the connections among food choices, health, sociocultural contexts, economies, and the environment. Such a step is important due to the many uses and impacts FBDGs have. Dietary guidelines can educate policy makers, program planners, researchers and the lay public about the interconnectedness of these domains, as well as the many, linked externalities of diets (e.g., more health issues and GHG emissions from animal products, food quality and soil degradation from monocultures, laborer health and animal welfare issues of factory farming). Education around such interconnections and impacts of diets—highlighted in part by FBGDs—has the potential to shift entire ontologies around food and consumption habits (Lang, 2017; Mazac and Tuomisto, 2020).

It is recognized that developing a framework for application internationally, especially across cultures and low-, middle-, and high-income countries, is challenging as there are different and multiple sociocultural, economic, and environmental factors in play (Downs et al., 2017; Ahmed et al., 2019). However, sustainable FBDGs will not mean "globally uniform diets, but culturally appropriate expressions of the same ecological and nutritional baselines" which could vary regionally and locally (Lang, 2017), p. 45. Using the Sustainability in FBDGs Framework and incorporating sustainability considerations in FBDGs will not mean an end to choice (as some might argue), but would, in fact, be a way for eaters to question the pervasive and strong influence over food tastes by commercial advertising and industry, who wield large budgets and lobbies to promote often unsustainable dietary patterns and foods (Lang, 2017).

The novelty of this study's framework is in the way it makes it possible to compare FBDGs both to the framework and each other; to ask what has been included, what is missing, and to see how many concepts have been integrated in other FBDGs to date. This framework can be foundational for cultivating the idea that diets have many dimensions and are interconnected such that diets must be approached with a systems lens. Integrating interconnected sustainability concepts into food guidelines can provide a means for meeting international calls for sustainability and addressing global progress toward the UN's 2015 Sustainable Development Goals (SDGs) (United Nations, 2015; Lang, 2017).

Applicability of the Sustainability in FBDGs Framework

This study supports the call proposed by Ahmed et al. (2019), to apply and develop integrative frameworks and addresses the lack of previous work depicting the interconnections of sustainability dimensions/sub-dimensions. The application of this study's framework can help those developing future FBDGs in the promotion of sustainable, bio- and culturally diverse diets that are appropriate to the country context. The framework may be used as an approach to assess the interconnected inclusion of sustainability domains in FBDGs that already exist (as illustrated by this study and by Ahmed et al., 2019).

This framework may also guide interconnected sustainability consideration in future FBDGs development. To apply the framework presented in this study, developers can begin by identifying the domains they wish to consider (e.g., health and nutrition & food security and agriculture), or any combination of such. Then, the concepts within those domains can be emphasized based on the context and considerations of that country. The definitions and examples of each domain (found in **Table S1**) can assist developers in selecting and formulating recommendations. Together with expert nutrition advice and rigorous evidence, this framework can be used to develop and guide recommendations for sustainable diets. Developers may apply the framework to assist in integrating sustainability domains into FBDGs through following examples given here, including various stakeholders as in these selected FBGDs, and applying this study's coding process to check and add to the interconnected nature of statements for sustainability consideration.

Countries currently without food guides can use this framework to address the various components of sustainable dietary guidance in their development process when they engage with multiple sectors, ministries, and experts. When applying the framework in different countries (e.g., low-, middle-, and high-income) the framework will help developers to address different, potentially overlapping issues, reflective of the country context. However, recommendations of sustainable dietary practices in FBDGs must navigate contextual differences. FBDGs must reflect variations in local climate and agricultural practices, nutritional needs of the population, as well as present culturally relevant dietary advice. It is recognized that different countries, regions, and even communities and individuals will have different values, practices, and barriers when it comes to how and what to eat (Desmarais and Wittman, 2014; van Dooren et al., 2014; Lang, 2017; Lang and Mason, 2017; Willett et al., 2019), which will change or make irrelevant the implementation of this framework.

Study Limitations and Future Directions

The framework adapted in this study does not address or evaluate the strength of specific policies or recommendations for influencing a sustainable diet. For example, Germany's FBDGs included four of the five domains, and 17% of the concepts. Yet, these numbers do not give an indication of the strength or impact of the recommendations made or exactly how explicit the connections to sustainability were. Simply finding the presence or absence of a concept does not compel or imply dietary change in a sustainable direction. A challenge of developing policies or guidelines is that they do not necessarily translate into immediate or effective action (Downs et al., 2017). Even if we identify recommendations made in the guidelines that have actions associated with them, evaluating impact is often not straightforward.

The framework is limited to identifying concepts and domains included in FBDGs based on the emphases of sustainability explicit in the final, publicly available versions of the guidelines. We have no deeper indication of the possible sustainability considerations made by policymakers and guideline developers throughout the development process. For example, the concepts of land tenure and on farm food loss were not found in any of the FBDGs in this analysis and were removed from this framework. These concepts are perhaps not immediately relevant to food guidelines—as they may be for food policies upon which Downs et al. (2017) was formulated. Though it was designed to be useful in diverse settings with little normative language, when this framework is applied in the future in different situations, adaptations will need to be made to reflect the country context and level of FBDGs development in the past (from none in many developing countries to well-established in countries such as the United States) (Gonzalez Fischer and Garnett, 2016; Herforth et al., 2019).

This study is also limited in that there was only funding, time, and resources available for one English speaking coder to conduct the document review, leading to uncertainty in categorization of the concepts. With only one coder, there is a chance that differing interpretations of where concepts should be placed in the framework were overlooked. Further, this study was limited to the inclusion of one focus group with 12 food system sustainability experts; more and different groups may have added or subtracted from the framework creating different concept or domains. Therefore, future work would benefit by conducting a formal reliability assessment, including the examination of non-English language FBDGs, and cross validating the content of the framework domains. Still, the qualitative application and validation of previous work (Downs et al., 2017; Ahmed et al., 2019) is step forward adding nuance and confirming the key findings proposed by earlier work in this field. There remains a need for further studies to monitor future FBDGs progress and to compare changes over time. Studies which build upon these analyses may provide additional guidance on integrating sustainability concepts and informing future approaches for applying these frameworks to policymaking.

Another limitation is that there remains no agreement in the literature on approaches for weighting of the different concepts or what is most important to emphasize in sustainable dietary recommendations. Raw quantification of concept inclusion is therefore less relevant than deeper, qualitative examination regarding contextual inclusion of sustainability domains. Another approach would be to set thresholds for different factors as an aim to reach a desired state in all domains following the concept of doughnut economics (Raworth, 2017). The trade-offs and thresholds from the environment, health, and ethical perspectives would have to be addressed in greater depth in another analysis that would be a possible future direction.

Much more work is needed in the field, to identify the indicators of change and measure impacts of including sustainability in FBDGs. Further evaluation is needed of how and why concepts related to sustainability were included or excluded. Such motivations behind concept inclusion are important for developing policy approaches which include sustainability domains in FBGDs in the future.

Conclusion: Beyond Sustainability in FBDG

Sustainability concepts have been recently included and published in at least 12 English-language FBDGs internationally, developed since 2011 in two supporting documents, and since 2016 in at least 10 official guidelines. This framework described here shows that sustainability was considered in FBDGs in interconnected ways. FBDGs internationally, such as in Qatar, Sweden, Brazil, Germany, and Canada, have included stakeholders and integrated interconnected domains that include sustainability in the guidelines for their respective countries.

We are at a critical juncture where there is some scholarship (Ahmed et al., 2019) and incorporation of sustainability in FBDGs, heeding earlier calls (Gussow and Clancy, 1986; World Health Organization Food Agriculture Organization of the United Nations, 1996) and recent recommendations made by international governing bodies and global reports (Gonzalez Fischer and Garnett, 2016; Willett et al., 2019). Embracing the possibility of "healthy diets from sustainable food systems" (Willett et al., 2019), p. 1, countries with dietary guidelines that include sustainability principles have started to address the crucial and immediate challenge of shifting diets (Mbow et al., 2019). Lessons from these countries can help to inform the continued international efforts needed to reduce the impact of food systems on sustainable futures for the planet.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR'S NOTE

The analysis for this study was originally carried out and based on work done by RM for an M.Sc. thesis (Mazac, 2019) and no additional funding was available to expand the sample to include non-English language FBDGs or those developed after the completion of the initial 2019 analysis.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the study led by RM. RM organized the data collection, performed the qualitative analysis, and wrote the full manuscript. All authors contributed to study design, manuscript review and revision, and approved the submitted version.

FUNDING

RM was funded for this work as a graduate student through faculty scholarships and university awards at the University of British Columbia. The final drafting, editing, and dissemination of this work was funded by the Research Funds of the University of Helsinki. JB received funding as a 2020-2021 Wall Scholar from the Peter Wall Institute for Advanced Studies at the University of British Columbia.

ACKNOWLEDGMENTS

Final edits and support for publishing were provided by Dr. Hanna L. Tuomisto. We want to give thanks to the sustainability educators and professionals for the formative feedback on this framework. Acknowledgment is owed for edits, reviews, and support from Dr. Quentin Geissman, Dr. Yumi Kobayashi, Chelsea Gowton, and Mirah Valdes.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.544072/full#supplementary-material

REFERENCES

Ahmed, S., Downs, S., and Fanzo, J. (2019). Advancing an integrative framework to evaluate sustainability in national dietary guidelines. *Front. Sustain. Food Syst*. 3:76. doi: 10.3389/fsufs.2019.00076

Aleksandrowicz, L., Green, R., Joy, E. J., Smith, P., and Haines, A. (2016). The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. *PLoS ONE* 11:e0165797. doi: 10.1371/journal.pone.0165797

Behrens, P., Kiefte-de Jong, J., Bosker, T., Rodrigeues, J., de Koning, A., and Arnold, T. (2017). Evaluating the environmental impacts of dietary recommendations. *Proc. Natl. Acad. Sci. U.S.A.* 114, 13412–13417. doi: 10.1073/pnas.1711889114

Burlingame, B., and Dernini, S. (2012). *Sustainable Diets and Biodiversity Directions and Solutions for Policy, Research and Action*. Rome: United Nations.

Campbell, J. L., Quincy, C., Osserman, J., and Pedersen, O. K. (2013). Coding in-depth semistructured interviews: Problems of unitization and intercoder reliability and agreement. *Sociol. Methods Res.* 42, 3294–3320. doi: 10.1177/0049124113500475

Department of Health (2012). *French National Nutrition and Health Program 2011–2015*. Paris: Ministry of Health.

Desmarais, A. A., and Wittman, H. (2014). Farmers, foodies and first nations: Getting to food sovereignty in Canada. *J. Peasant Stud*. 41, 61153–61173. doi: 10.1080/03066150.2013.876623

Donini, L. M., Dernini, S., Lairon, D., Serra-Majem, L., Amiot, M., del Balzo, V., et al. (2016). A consensus proposal for nutritional indicators to assess the sustainability of a healthy diet: The Mediterranean diet as a case study. *Front. Nutr*. 3:37. doi: 10.3389/fnut.2016.00037

Downs, S. M., Payne, A., and Fanzo, J. (2017). The development and application of a sustainable diets framework for policy analysis: a case study of Nepal. *Food Policy* 70, 40–49. doi: 10.1016/j.foodpol.2017.05.005

Drisko, J. W., and Maschi, T. (2015). *Content Analysis*. Oxford: Oxford University Press. doi: 10.1093/acprof:oso/9780190215491.001.0001

Dye Gussow, J. (1999). Dietary guidelines for sustainability: twelve years later. *J. Nutr. Educ.* 31, 4194–4200. doi: 10.1016/S0022-3182(99)70441-3

Entman, R. M. (1993). Framing: Toward clarification of a fractured paradigm. *J. Nutr. Commun*. 43, 451–458. doi: 10.1111/j.1460-2466.1993.tb01304.x

FAO (2014). *ICN2 International Conference on Nutrition: Better Nutrition, Better Lives*. Rome: Food and Agriculture Organisation. Available online at: http://www.fao.org/about/meetings/icn2/en/

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., et al. (2011). Solutions for a cultivated planet. *Nature* 478, 7369337–7369342. doi: 10.1038/nature10452

Food and Agriculture Organization of the United Nations (2019). *Food-Based Dietary Guidelines*. Available online at: http://www.fao.org/nutrition/education/food-dietary-guidelines/home/en/ (accessed April 20, 2018).

Garnett, T., Appleby, M., and Balmford, A. (2014). *What Is a Sustainable Healthy Diet*. Oxford: Food Climate Research Network.

German Nutrition Society (2013). *Ten Guidelines for Wholesome Eating and Drinking From the German Nutrition Society*. Bonn: German Nutrition Society. Available online at: https://www.dge.de/ernaehrungspraxis/vollwertige-ernaehrung/10-regeln-der-dge/10-guidelines-of-the-german-nutrition-society/?L=0

Godfray, H. C. J., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Nisbett, N., et al. (2010). The future of the global food system. *Philos. Trans. R. Soc. Lond. B Biol. Sci*. 365, 2769–2777 doi: 10.1098/rstb.2010.0180

Gonzalez Fischer, C., and Garnett, T. (2016). *Plates, Pyramids, Planet Developments in National Healthy and Sustainable Dietary Guidelines: A State of Play Assessment*. Rome: FAO and the Environmental Change Institute & The Oxford Martin Programme on the Future of Food, The University of Oxford.

Gussow, J. D., and Clancy, K. L. (1986). Dietary guidelines for sustainability. *J. Nutr. Educ.* 18, 11–15. doi: 10.1016/S0022-3182(86)80255-2

Hallström, E., Carlsson-Kanyama, A., and Börjesson, P. (2015). Environmental impact of dietary change: a systematic review. *J. Clean. Product*. 91, 1–11. doi: 10.1016/j.jclepro.2014.12.008

Health Canada (2019). *Canada's Dietary Guidelines*. Ottawa, ON: Health Canada.

Health Council of the Netherlands (2015). *Dutch Dietary Guidelines 2015*. Hague: Health Council of the Netherlands.

Herforth, A., Arimond, M., Álvarez-Sánchez, C., Coates, J., Christianson, K., and Muehlhoff, E. (2019). A global review of food-based dietary guidelines. *Adv. Nutr*. 10, 590–605. doi: 10.1093/advances/nmy130

Ingram, J. (2011). A food systems approach to researching food security and its interactions with global environmental change. *Food Security* 3, 4417–4431. doi: 10.1007/s12571-011-0149-9

Jenkin, G. L., Signal, L., and Thomson, G. (2011). Framing obesity: The framing contest between industry and public health at the new zealand inquiry into obesity. *Obes. Rev*. 12, 121022–121030. doi: 10.1111/j.1467-789X.2011.00918.x

Johnston, J. L., Fanzo, J. C., and Cogill, B. (2014). Understanding sustainable diets: a descriptive analysis of the determinants and processes that influence diets and their impact on health, food security, and environmental sustainability. *Adv. Nutr*. 5, 4418–4429. doi: 10.3945/an.113.005553

Kesse-Guyot, E., Chaltiel, D., Wang, J., Pointereau, P., Langevin, B., Allès, B., et al. (2020). Sustainability analysis of french dietary guidelines using multiple criteria. *Nat. Sustainab*. 3, 377–385. doi: 10.1038/s41893-020-0495-8

Krippendorff, K. (2004). *Content Analysis: An Introduction to its Methodology, 2nd Edn*. Newbury Park, CA: Sage publications.

Lang, T. (2017). *Re-fashioning food systems with sustainable diet guidelines: Towards a SDG2* strategy.

Lang, T., and Mason, P. (2017). Sustainable diet policy development: implications of multi-criteria and other approaches, 2008–2017. *Proc. Nutr. Soc*. 77, 331–346. doi: 10.1017/S0029665117004074

Macdiarmid, J. I. (2013). Is a healthy diet an environmentally sustainable diet? *Proc.Nutr.Soc*. 72, 113–120. doi: 10.1017/S0029665112002893

Mayring, P. (2004). "Qualitative content analysis," in *A Companion to Qualitative Research*, Vol. 1 (Sage), 159–176.

Mazac, R. (2019). *Examining Sustainability in Food-Based Dietary Guidelines: An International Comparison and Systems Thinking Framework for Sustainable Dietary Guideline Development*. Vancouver, BC: University of British Columbia.

Mazac, R., and Tuomisto, H. L. (2020). The post-Anthropocene diet: navigating future diets for sustainable food systems. *Sustainability* 12:2355. doi: 10.3390/su12062355

Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., et al. (2019). "Chapter 5: food security," in *IPCC Special Report on Climate Change and Land*. Available online at: https://www.ipcc.ch/site/assets/uploads
McGinnis, J. M., Gootman, J. A., and Kraak, V. I. (2006). *Food Marketing to Children and Youth*: *Threat Or Opportunity*? Washington, DC: National Academies Press.
Ministry of Health of Brazil (2015). *Dietary Guidelines for the Brazilian Population*. Brazil: Secretariat of Health Care Primary Health Care Department.
National Health and Medical Research Council (2013). *Australian Dietary Guidelines*. Canberra, ACT: National Health and Medical Research Council.
Nordic Council of Ministers (2014). *Nordic Nutrition Recommendations 2012: Integrating Nutrition and Physical Activity, 5th Edn*. Copenhagen: Nordisk Ministerråd.
Public Health England (2016). *Eatwell Guide Booklet*. London: Public Health England.
Raworth, K. (2017). *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist.* Chelsea, VT: Chelsea Green Publishing.
Rizvi, S., Pagnutti, C., Fraser, E., Bauch, C., and Anand, M. (2018). Global land use implications of dietary trends. *PLoS ONE* 8:e0200781. doi: 10.1371/journal.pone.0200781
Röös, E., Karlsson, H., Witthöft, C., and Sundberg, C. (2015). Evaluating the sustainability of diets–combining environmental and nutritional aspects. *Environ. Sci. Policy* 47, 157–166. doi: 10.1016/j.envsci.2014.12.001
Sabaté, J., Harwatt, H., and Soret, S. (2016). Environmental nutrition: a new frontier for public health. *Am. J. Public Health* 106, 5815–5821. doi: 10.2105/AJPH.2016.303046
Seed, B. (2015). Sustainability in the Qatar national dietary guidelines, among the first to incorporate sustainability principles. *Public Health Nutr*. 18, 132303–132310. doi: 10.1017/S1368980014002110
Seed, B., and Rocha, C. (2018). Can we eat our way to a healthy and ecologically sustainable food system? *Canad. Food Stud.* 5, 3182–3207. doi: 10.15353/cfs-rcea.v5i3.258
Springmann, M., Godfray, H. C. J., Rayner, M., and Scarborough, P. (2016). Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc. Natl. Acad. Sci. U.S.A.* 113, 154146–154151. doi: 10.1073/pnas.1523119113
Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., et al. (2015). Planetary boundaries: guiding human development on a changing planet. *Science* 347:1259855. doi: 10.1126/science.1259855
Supreme Council of Health (2015). *Qatar Dietary Guidelines*. Doha: Public Health Department.
Swedish National Food Agency (2015). *Find Your Way to Eat Greener, Not Too Much and Be Active*. Sweden: Livsmedelsverket.
Syed, M., and Nelson, S. C. (2015). Guidelines for establishing reliability when coding narrative data. *Emerg. Adulthood* 3, 6375–6387. doi: 10.1177/2167696815587648
Tilman, D., and Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature* 515, 7528518–7528522. doi: 10.1038/nature13959
Trevena, H., Kaldor, J. C., and Downs, S. M. (2015). Sustainability does not quite get the attention it deserves: synergies and tensions in the sustainability frames of australian food policy actors. *Nature* 18, 132323–132332. doi: 10.1017/S136898001400295X
Tubiello, F. N., Salvatore, M., Cóndor Golec, R. D., Ferrara, A., Rossi, S., Biancalani, R., et al. (2014). *Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks*. Rome: Statistics Division, Food and Agriculture Organization.
Tuomisto, H. L. (2019). The complexity of sustainable diets. *Nat. Ecol. Evol*. 3, 720–721. doi: 10.1038/s41559-019-0875-5
U.S. Department of Health, Human Services, and U.S. Department of Agriculture (2015). *2015–2020 Dietary Guidelines for Americans, 8th Edn*. Washington, DC: U.S. Department of Health; Human Services; U.S. Department of Agriculture.
UN FAO (2010). *International Scientific Symposium: Biodiversity and Sustainable Diets United Against Hunger*. Rome: Unite Nations.
UN FAO (2018). *The State of World Fisheries and Aquaculture*. Rome: Food and Agriculture Organization of the United Nations.
United Nations (2015). *Sustainable Development Goals*. Available online at: https://sustainabledevelopment.un.org/sdgs (accessed October 29, 2018).
United Nations (2017). *WHO | United Nations Decade of Action on Nutrition. World Health Organization*. Rome: United Nations. Available online at: http://www.who.int/nutrition/decade-of-action/en/ (accessed February 2, 2018).
van Dooren, C., Marinussen, M., Blonk, H., Aiking, H., and Vellinga, P. (2014). Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns. *Food Policy* 44, 36–46. doi: 10.1016/j.foodpol.2013.11.002
Vermeulen, S. J., Campbell, B. M., and Ingram, J. S. (2012). Climate change and food systems. *Annu. Rev. Environ. Resour.* 37, 195–222. doi: 10.1146/annurev-environ-020411-130608
Wang, S., Lay, S., Yu, H., and Shen, S. (2016). Dietary guidelines for chinese residents (2016): Comments and comparisons. *J. Zhejiang Univ. Sci. B* 17, 9649–9656. doi: 10.1631/jzus.B1600341
Wegener, J., Fong, D., and Rocha, C. (2018). Education, practical training and professional development for public health practitioners: A scoping review of the literature and insights for sustainable food system capacity-building. *Public Health Nutr*. 21, 1771–1780. doi: 10.1017/S1368980017004207
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the anthropocene: The EAT–Lancet commission on healthy diets from sustainable food systems. Lancet. 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4
World Health Organization and Food and Agriculture Organization of the United Nations (1996). *Preparation and Use of Food-Based Dietary Guidelines*. Geneva.
Zagmutt, F. J., Pouzou, J. G., and Costard, S. (2019). The EAT–Lancet commission: a flawed approach? *Lancet* 394, 1141–1142. doi: 10.1016/S0140-6736(19)31903-8

Conflict of Interest: BS is the principal at B. Seed Consulting.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

REVIEW
published: 13 January 2022
doi: 10.3389/fsufs.2021.822263

A Scoping Review of Indicators for Sustainable Healthy Diets

Megan R. Harrison, Giulia Palma, Tomás Buendia, Marta Bueno-Tarodo, Daria Quell and Fatima Hachem*

Food and Nutrition Division, Food and Agriculture Organization of the United Nations, Rome, Italy

Introduction: Diets are currently unsustainable in many countries as evidenced by the growing burden of malnutrition, degradation of natural resources, contributions to climate change, and unaffordability of healthy diets. Agreement on what constitutes a healthy and sustainable diet has been debated. In 2019, FAO and WHO published the Sustainable Healthy Diets Guiding Principles, defining what qualifies as a sustainable healthy diet. While valuable, these principles require measurable indicators to support their operationalization. Our scoping review aims to describe how sustainable healthy diets have been assessed in the literature since 2010.

Methods: A search for English-language articles published in peer-reviewed journals was conducted from January 2010 through February 2020 across three databases. Out of the 504 articles initially identified, 103 articles were included. Metadata were extracted from each article on: publication year, country of study, study aims, methods, main data sources, indicators used to assess sustainable healthy diets, reported indicator strengths or limitations, and main study findings. A qualitative content analysis identified major conceptual themes across indicators and their frequency of use.

Findings: From the 103 empirical articles included in our review, 57.3% were published after 2017. Most studies were carried out in high-income countries (74%). Approximately 42% of the articles assessed the sustainability of diets using solely health and environmental indicators; <25% assessed the sustainability of diets across health, environmental, and sociocultural aspects of sustainability. We found a substantial number of unique indicators used for assessing health ($n = 82$), environmental ($n = 117$), and sociocultural ($n = 43$) aspects of diets. These indicators covered concepts related to health outcomes, aspects of diet quality, natural resources, climate change, cultural acceptability, and cost of diets. The preponderance of indicators currently used in research likely poses challenges for stakeholders to identify the most appropriate measures.

Conclusion: Robust indicators for sustainable healthy diets are critical for understanding trends, setting targets, and monitoring progress across national and sub-national levels. Our review highlights the geographical imbalance, the narrow focus on health and environmental aspects, and the lack of common measures used in research. Measures registries could provide the decision-support needed by stakeholders to aid in the indicator selection process.

Keywords: sustainable healthy diets, indicators and metrics, sustainable diets, dietary assessment, sociocultural indicators, environmental indicators, dietary indicators

Edited by:
Bradley George Ridoutt, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

Reviewed by:
Sinead Boylan, The University of Sydney, Australia
Florent Vieux, MS-Nutrition, France

****Correspondence:***
Megan R. Harrison
megan.harrison@fao.org

Specialty section:
This article was submitted to Nutrition and Sustainable Diets, a section of the journal Frontiers in Sustainable Food Systems

Received: *25 November 2021*
Accepted: *14 December 2021*
Published: *13 January 2022*

Citation:
Harrison MR, Palma G, Buendia T, Bueno-Tarodo M, Quell D and Hachem F (2022) A Scoping Review of Indicators for Sustainable Healthy Diets. Front. Sustain. Food Syst. 5:822263. doi: 10.3389/fsufs.2021.822263

INTRODUCTION

The Unsustainability of Current Diets

Combatting malnutrition in all its forms—including undernutrition, micronutrient deficiency, overweight, and obesity—and reducing the burden of diet-related non-communicable diseases (NCDs) are two of the major global challenges of the twenty-first century. The recent State of Food Security and Nutrition report confirms the rise in prevalence of global hunger over the past 5 years (FAO, 2020). Undernutrition for children aged <5 years persists in the forms of stunting (144 million), wasting (47 million), and underweight (88 million) (UNICEF/WHO, 2020; WHO, 2020). At the same time, ∼2 billion adults and 340 million children (aged 5–19 years) are currently overweight or obese (Abarca-Gómez et al., 2017).

Malnutrition has serious, costly, and long-lasting health, social, and developmental impacts for individuals and countries. During childhood, undernutrition is associated with higher risks of infectious diseases, lower cognitive scores, and poor school achievement (Adair et al., 2013; Black et al., 2013; Sacchi et al., 2020). Obesity also poses immediate health risks (Lloyd et al., 2012; Narang and Mathew, 2012; Cote et al., 2013; Mohanan et al., 2014; Bacha and Gidding, 2016; Di Bonito et al., 2018) and often persists into adulthood with increased risk of non-communicable diseases such as coronary heart disease, stroke, type 2 diabetes, and several types of cancer (Guh et al., 2009; Lauby-Secretan et al., 2016). Micronutrient deficiencies, which can occur across age and body weight categories, are a particular concern for women of reproductive age and young children (Black et al., 2013; Zimmermann, 2016). Malnutrition also carries large direct and indirect costs to individuals and national economies as it has direct impact on human capital. While the causes of malnutrition are complex, poor diet is a leading contributor to the global burden of diet-related diseases and is responsible for more deaths than any other risk factor globally (Afshin et al., 2019). Suboptimal diets are generally low in fibers, fruits, vegetables, legumes, whole grains, nuts and seeds, milk, seafood, calcium, and healthy fats (omega 3 fatty acids, polyunsaturated fatty acids) and high in *trans*-fatty acids, sodium, red or processed meat, and sugar-sweetened beverages (Afshin et al., 2019).

Beyond delivering suboptimal and inequitable population health outcomes, current food consumption patterns place a significant strain on land, water, air, and other natural resources. Agricultural production is responsible for 40% of global land use and 70% of fresh water withdrawals (Foley et al., 2005; Molden, 2013). The conversion of natural ecosystems to cropland and pasture land is one of the greatest drivers of biodiversity loss (Tilman et al., 2017). The over-application and misuse of fertilizers results in nitrogen and phosphorus runoff, fueling the eutrophication of lakes, rivers, and coastal areas and creating "dead zones" (Diaz and Rosenberg, 2008). Current consumption patterns contribute to climate change, with global food systems accounting for up to 29% of global greenhouse gas emissions (GHGE) (Vermeulen et al., 2012). Although malnutrition in all its forms is the largest cause of lost health in the world (Swinburn et al., 2019), the health effects of climate change will considerably compound these health challenges in the near future through impacts on crop yields, nutrient quality of foods, and changing land and ocean temperatures (Myers et al., 2017).

Healthy diets remain unaffordable for many people in almost every region of the world (FAO, 2020). Nutrient-dense foods are often more expensive than starchy staples and foods high in sugar and fat, especially in low-income countries (Headey and Alderman, 2019). At the same time, current production levels of nutrient-dense foods like fruits and vegetables are inadequate to meet minimum global dietary recommendations for the global population (Mason-D'Croz et al., 2019). Meanwhile, 32% of food produced globally is lost or goes to waste (FAO, 2011). At the same time, food choices and food-related behaviors are deeply connected to social and economic expressions of identity, gender, religion, preferences, and cultural meaning (Monterrosa et al., 2020). For example, in many societies food symbolizes social standing, where foods consumed by the affluent symbolize superiority while less-prestigious foods may be associated with poverty (Cloete and Idsardi, 2013; Monterrosa et al., 2020). Religious or spiritual views can determine which foods are good or bad, holy or unholy, clean or dirty (Fieldhouse, 2013). The sustainability of any diet is influenced by sociocultural factors such as conditional food preferences, attitudes, values, social structures, cultural practices, and assets just to name a few (Monterrosa et al., 2020). Any attempt to transition toward more sustainable healthy diets must take into account the sociocultural factors that underpin consumption patterns.

The History of Sustainable Healthy Diets

The term "sustainable diets" is not new. It was first introduced in the literature in Gussow and Clancy (1986), where the authors argued the importance of optimizing individual diets for both human health and the protection of natural resources (Gussow and Clancy, 1986). The concept obtained little attention in the ensuing years, as the global community focused on reducing hunger, undernutrition, and food insecurity. This focus led to policies centered around increasing agricultural industrialization, production intensification, and food globalization, often with little consideration for how such policies may exacerbate existing inequalities or negatively impact natural resources (Lang, 2010). In 2010, a widely accepted definition of sustainable diets was coined stating, "Sustainable diets are those diets with low environmental impacts which contribute to food and nutrition security and to a healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources" (Burlingame and Dernini, 2012). This definition broadened the understanding of sustainable diets to be more comprehensive, encompassing aspects beyond human health and natural resources alone.

In 2014, the Second International Conference on Nutrition highlighted the challenges and urgency of transforming food systems to deliver healthy diets in a sustainable manner given the growing double burden of malnutrition (CIHEAM/FAO, 2015). Conceptual frameworks were developed showing the relationship between food systems and nutrition (HLPE, 2017). Calls for transforming food systems to become more sustainable and capable of ensuring healthy diets began to be globally embraced. The role of diets as a lever for sustainability was highlighted in many publications (Johnston et al., 2014; Gustafson et al., 2016; Downs et al., 2017). However, this role was often ill-defined; at times, it focused only on a single issue, while at other times it included multiple environmental, economic, and societal goals. The lack of agreement by countries on what constitutes healthy diets and more so on what constitutes healthy diets that are sustainable led the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) to produce the Sustainable Healthy Diets Guiding Principles in 2019. While the previous definition included health considerations, in its application, economic and environmental goals of diets were often given preeminence. This new definition placed health at the forefront of consideration, while still underscoring the need to consider all aspects. The report defined sustainable healthy diets as, "dietary patterns that promote all dimensions of individuals' health and wellbeing, have low environmental pressure and impact, are accessible, affordable, safe and equitable, and are culturally acceptable" and includes 16 principles grouped under three aspects of sustainability: health, environmental and sociocultural that must be considered together for achieving sustainable healthy diets (FAO WHO, 2019).

Challenges to Quantifying Sustainable Healthy Diets

The 16 guiding principles of sustainable healthy diets aim to provide flexible guidance to countries for policy and program implementation, taking into account different local contexts. However, for them to be operationalized, the values laid out in the 16 guiding principles must correspond to measures capable of analyze trends, set targets, and monitor progress at national or subnational levels. Clear indicators and methods for measuring the different aspects of sustainable healthy diets are necessary for (1) building the evidence base to support guidelines and policies for the promotion of sustainable healthy diets and (2) monitoring and evaluating progress toward national and subnational targets for transitioning toward sustainable healthy diets. In order to build a compendium of indicators for sustainable healthy diets, there is a need to identify and describe the measures currently being used in research on sustainable healthy diets. Previous literature reviews have partially examined measurements of sustainable diets, but fell short of investigating how the concept of sustainable diets was defined by researchers and did not report on any strength or limitation of proposed measures (Jones et al., 2016; Eme et al., 2019). Our goal was to carry out a literature review of empirical studies to describe how sustainable healthy diets have been defined and measured in the research literature. This review was designed to address the questions: (1) how have sustainable healthy diets been defined in the scientific literature since 2010 and (2) what range of indicators is currently in use for assessing sustainable healthy diets and with what frequency are these indicators being used?

METHODS

Study Design

Given the complexity of sustainable healthy diets and the vast number of indicators proposed and reported in the academic literature, a modified scoping review design was adopted (Peters et al., 2015). As opposed to systematic literature reviews, which seek to answer a very specific set of questions, scoping reviews aim to determine what kind of evidence (quantitative or qualitative) is available on a particular topic and synthesize these data through mapping or charting. Since scoping reviews are broader in nature, they can be particularly useful for bringing together evidence from heterogeneous sources. Existing indicators of sustainable healthy diets reported in peer-reviewed literature were compiled and categorized. The indicator compilation was conducted between March and August 2020.

Literature Search Strategy and Study Selection

A search for English-language articles published in peer-reviewed journals between January 2010 and February 2020 was performed using the electronic databases PubMed, Science Direct, and Web of Science. The start date for the search was based on the year the definition of sustainable diets was published (Burlingame and Dernini, 2012). The search was undertaken with a uniform set of search terms, along with Boolean logic modified to the select database (**Supplementary Table 2**).

Following recommended protocols for scoping reviews, at least two reviewers were involved in the abstract and full-text screening of each article in order to minimize reporting bias (Peters et al., 2015). The database search resulted in 504 articles. After removing duplicates, 443 articles remained. The initial round of title and abstract screening yielding 199 eligible articles. A further round of full-text screening resulted in 103 original articles for inclusion in this review (**Figure 1**). Any conflicts between independent reviewers regarding the eligibility of articles for inclusion were resolved through discussions within the review team until consensus was reached. Criteria for exclusion are described in **Supplementary Table 3**.

Data Collection and Analysis

Papers included in this review were analyzed and data were extracted for details on the following variables: publication year, country of study, study aims, methods, main data sources, definitions of sustainable diets, indicators used to assess sustainable diets, reported justifications and limitations of select indicators by the study authors, and main study findings. Data extraction was completed by one of three reviewers for each article. Quality assurance checks on extracted data were completed by a second reviewer on approximately 75% of included articles to limit data extraction errors. Indicators were identified based on the data sources used and the empirical analysis undertaken as part of each study. For the purpose of this review, we defined "concepts" as the abstract phenomena or idea that was being studied while "indicators" were defined as quantitative or qualitative measures used to communicate information on that particular phenomena or idea. Variables, or

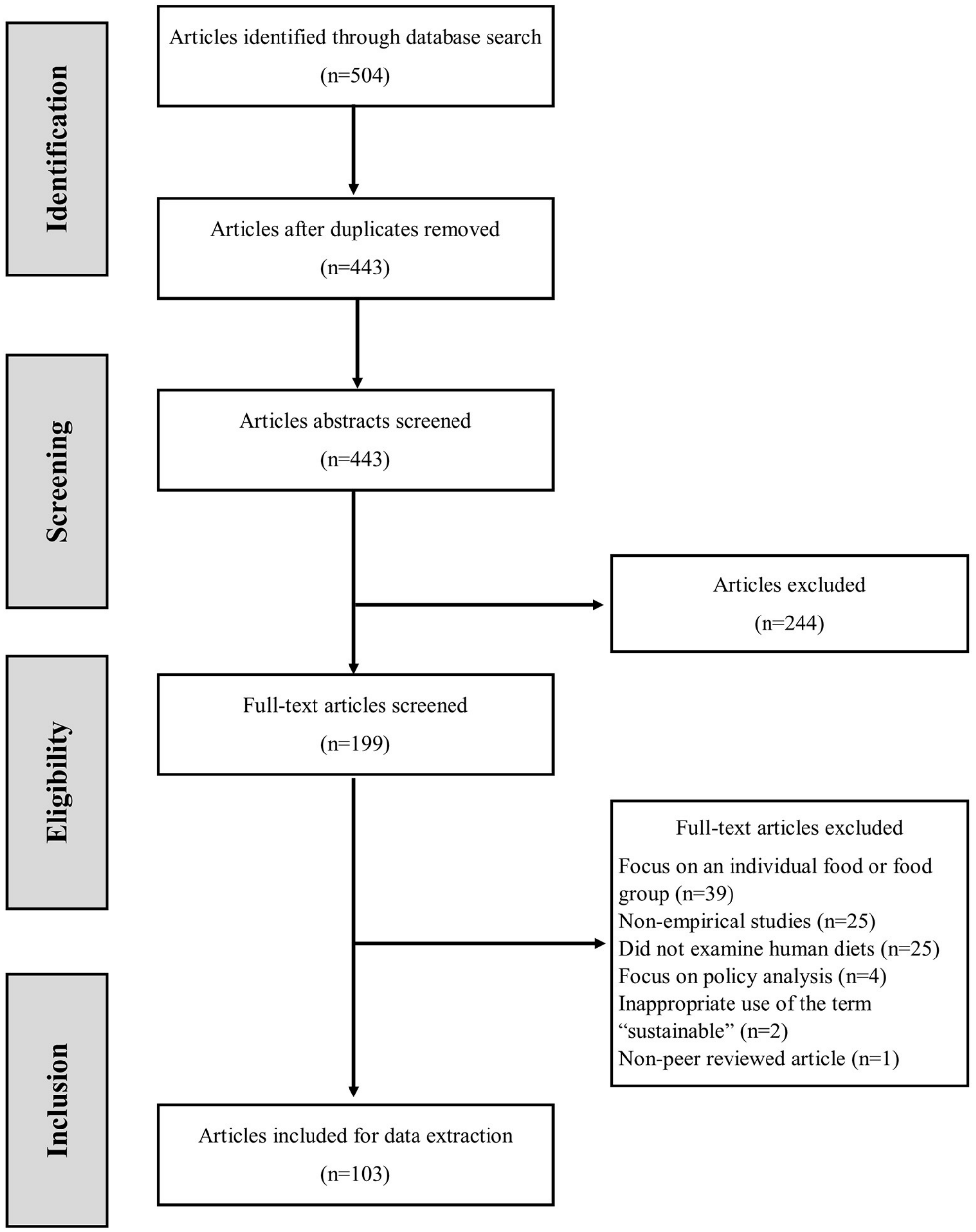


FIGURE 1 | PRISMA diagram of article identification and selection for qualitative analysis.

the value that an indicator takes on and its scale of measurement, were not extracted as part of our review. As part of the data extraction tool, all indicators were mapped to one of the three main aspects used to define sustainable healthy diets (i.e., health, environmental, and sociocultural aspects). All data were collected, stored, and analyzed in Microsoft Excel.

Given the heterogeneity of study designs related to sustainable healthy diets, the indicators used in assessing the sustainability of diets were evaluated on a qualitative and descriptive basis, rather than quantitatively. Following data extraction and cleaning, a qualitative content analysis was undertaken to identify major conceptual themes across indicators. Indicators were further grouped based on semantic similarities in order to synthesize the results presented below. The frequency of use for each indicators was calculated by conceptual theme. The total number of unique or non-repeating indicators was also calculated to provide insight on the range of diverse measurements being used by researchers. In line with standard scoping review practices, a formal assessment of the methodological quality of included studies was not performed (Peters et al., 2015). Therefore, although the main findings of each study are presented, weighing the quality of evidence for each study was outside the scope of this review.

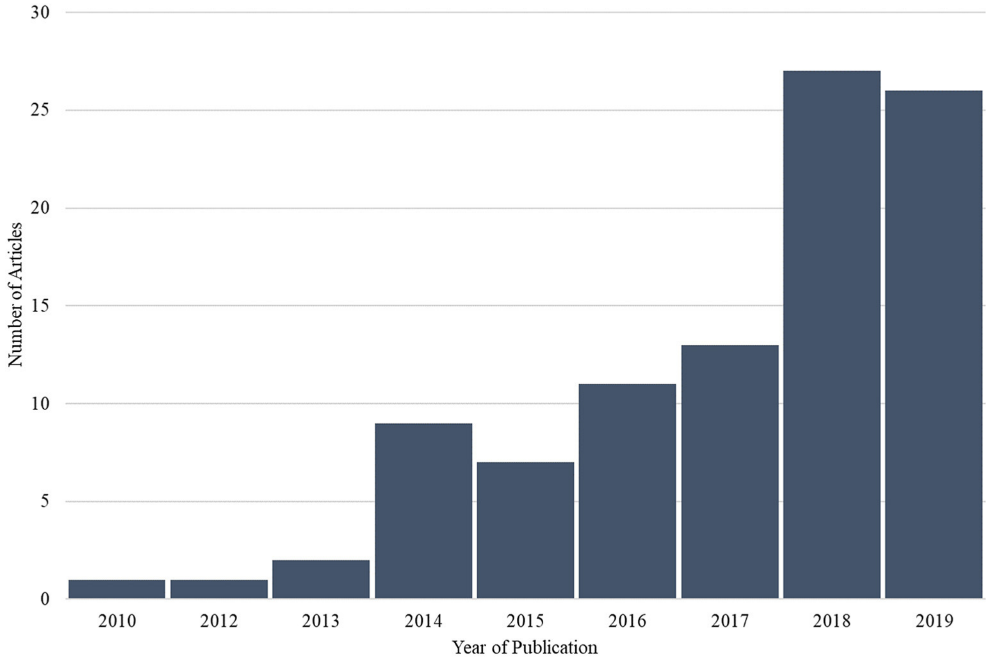


FIGURE 2 | Distribution of articles by year of publication, 2010–2019. Six articles identified between January–February 2020 are not pictured in the figure above, but were included in the scoping review.

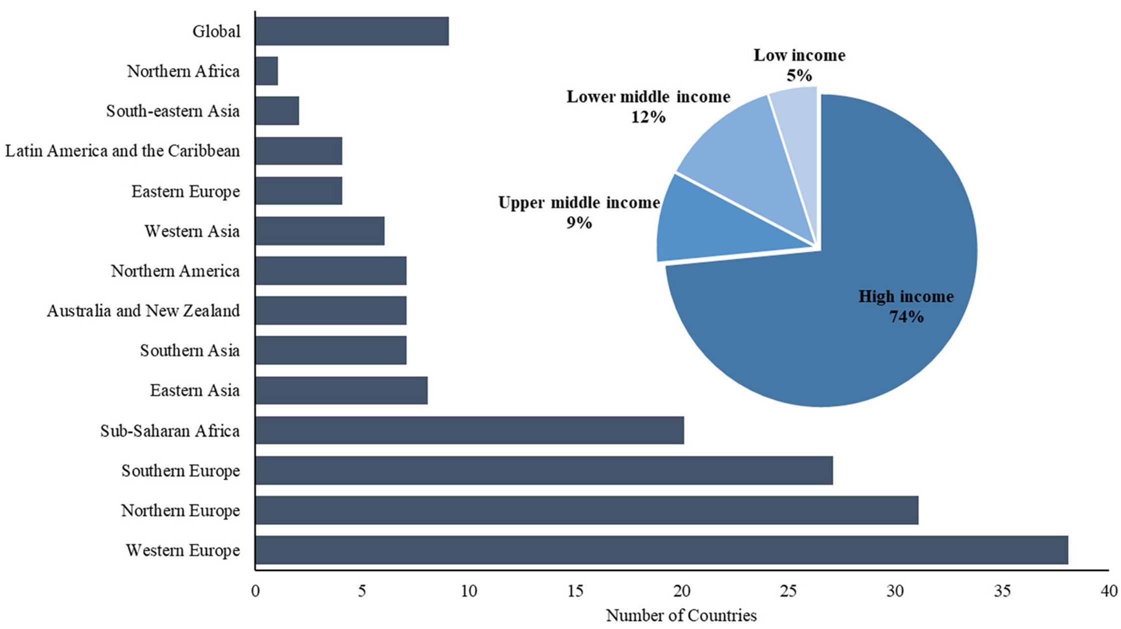


FIGURE 3 | Distribution of countries contributing data to included articles, by sub-region and income group. Sub-Region classification is based on the United Nations Statistics Division classification (UNSD, 2020). Income group classification is based on the World Bank's 2020 fiscal year classification (World Bank Country Lending Groups, 2020). The x axis shows the number of countries that contributed data to the included studies from the sub-region shown. Studies were classified as global if they included data from >36 countries.

TABLE 1 | Health indicators by concept measured and frequency of use in the scoping review.

Health indicators (n = 143)			
Concept		**Frequency count, *n***	**Examples**
Health outcomes		26	Avoided DALYs from cardiovascular disease, diabetes, and/or cancer; avoided premature death; prevalence of under-five childhood stunting (%); prevalence of under-five underweight (%)
Diet quality	Nutrient adequacy	22	% Population share with adequate nutrients; adequacy ratio for individual macro- and micronutrients; mean adequacy ratio; prevalence of inadequate micronutrient intake
	Nutrient density	16	NRD9.3 Index; NRF9.3 Index; density of overconsumed nutrients; Nutrient Balance score
	Moderation	12	Animal-to-plant energy ratio; animal-to-plant protein ratio; discretionary energy intake; excess red and processed meat consumption; mean excess ratio
	Diversity	9	Child Diet Diversity score; Diet Diversity Score; dietary species richness; Functional Diversity score
	Safety	1	Contaminant content of food
	Multiple concepts	47	Healthy Eating Index; PANDiet score; adequate total energy, macronutrient, and micronutrient intake; Diet Quality Index; SAIN:LIM ratio
Diet quantity		4	Non-discretionary energy intake; total energy availability; total energy intake
Other		6	Ratio of fruit and vegetable availability to recommended consumption; bio-conversion factors for food

TABLE 2 | Environmental indicators by concept measured and frequency of use in the scoping review.

Environmental indicators (n = 262)		
Concept	**Frequency count, *n***	**Examples**
Greenhouse gases	77	GHGE; carbon footprint; climate impact; food production GHGE; global warming impact; global warming potential; landfill GHGE; total CO_2 emissions
Water use	47	Blue water scarcity footprint; blue water footprint; freshwater use; gray water footprint; green water footprint; total water footprint; water consumption; water use
Land use	36	Land use; cropland use; ecological footprint; land occupation; land footprint; nature occupation
Toxicology	16	Respiratory inorganics; ecotoxicity; human toxicity; particulate matter
Energy use	16	Energy use; cumulative energy demand; energy consumption; fossil resource scarcity; non-renewable energy
Eutrophication	11	Eutrophication potential; freshwater eutrophication; marine eutrophication; marine eutrophication potential
Reactive nitrogen	9	Nitrogen application; nitrogen footprint; ammonia emissions; nitrogen loss
Acidification	9	Acidification; acidification potential; air acidification; terrestrial acidification potential
Ozone depletion	7	Ozone layer depletion; photochemical ozone creation potential; stratospheric ozone depletion
Biodiversity	5	Biodiversity damage potential; extinction rate; biodiversity loss from land use; regional biodiversity impacts due to land use occupation
Food waste	5	Food waste rate; household food waste; consumer-level food loss and waste
Phosphorus use	4	Phosphorus application; phosphorus cycle; phosphorus use
Other	20	Partial ReCiPe score; sustainability score; biosphere integrity; fish stock remaining; forest cover loss; GHGE-Land Use score; environmental impact score

RESULTS

This scoping review included 103 empirical studies, with the majority of these articles published after 2017 (57.3%) (**Figure 2**). The vast majority of studies were focused in high-income countries (74%), particularly Western Europe, Northern Europe, and Southern Europe (**Figure 3**). A summary of the 103 articles included in this review are listed in **Supplementary Table 1**. Indicators used to assess the sustainability of diets in each article were mapped to one of the three main aspects used to define sustainable. An overview of the health, environmental, and sociocultural indicators used for assessing the sustainability of diets can be found in **Tables 1–3**, respectively.

Definitions of Diets' Sustainability

Twenty-nine articles (28% of sample) referred to or cited the 2010 definition of sustainable diets. Sustainable diets were not explicitly defined in 60 articles (58% of sample). The remaining articles (n = 14; 14% of sample) offered an alternative definition of sustainable diets. Alternative definitions often considered only two out of the three aspects of sustainable healthy diets. Alternative definitions more frequently focused on health and environmental aspects, and neglected to mention the sociocultural aspect. **Supplementary Table 4** provides representative quotes for alternative definitions of sustainable diets proposed in the literature as found by this scoping review.

Methods and Data Sources Used Across Studies

Of the 103 articles included in the current review, 44 examined observed diets only (i.e., based on empirical data

TABLE 3 | Sociocultural indicators by concept measured and frequency of use in the scoping review.

Sociocultural indicators (n = 59)		
Concept	**Frequency count, *n***	**Examples**
Cultural acceptability	10	Acceptability; cultural acceptability; culture deviation index; respect for current dietary habits; social and cultural acceptability of diets
Animal welfare	3	Animal life years suffered; loss of animal lives; loss of morally adjusted animal lives
Satisfaction	3	Appreciation of meal; palatability; tastiness of meal
Attitudes	1	Environmental attitudes
Food security	1	Provision of adequate nutrition for a fair number of people
Cost of diets	24	Cost of diets; cost of meal; consumer costs; food expenditure; price of food; share of budget dedicated to food purchase; diet affordability; cost of nutrient adequacy
Environmental costs	7	Cost of environmental impact of diet; cost benefits attributable to environmental improvements; cost of GHGE embodied in food consumption; cost of environmental benefits
Health costs	4	Cost benefits attributable to health improvements; cost per DALY saved; obesity-related health expenditure; Health sector costs attributable to inadequate fruit and vegetable consumption and elevated BMI
Productivity costs	1	Productivity costs attributable to inadequate fruit and vegetable consumption and elevated BMI
Other	5	Accidents among farm workers; frequency of consumption of ready-made products; number of working hours for farmers; place of food purchase

and representative of actual population diets). Eighteen articles examined modeled diets only (i.e., those consistent with evidence-based recommendations or hypothetical scenarios) and 39 articles examined both observed and modeled diets. Multi-objective optimizations modeling, which was used in 12 articles, was one of the most common modeling methods employed. Multi-objective optimization modeling, also known as linear programming, is a mathematical technique used to minimize or maximize a linear function, depending on a series of defined constraints. It is commonly used in diet optimization studies. For the studies that aimed to improve diet-related health outcomes, most assumed health improvements would be achieved through adherence to evidence-based dietary recommendations. However, seven studies explicitly estimated improvements in health outcomes associated with different dietary scenarios. Dietary data came largely from national health and food consumption surveys collected at the individual level (e.g., Australian Health Survey, the Danish National Dietary Survey, and the French NutriNet-Santé study), data collected at the household level through household consumption and expenditure surveys (HCES), and data available at the national level through Food Balance Sheets (FAOSTAT).

Methods used for evaluating the environmental impacts of diets varied across studies. Life cycle assessment (LCA) was used in the majority of studies. LCA is a quantitative modeling approach used to estimate environmental impacts across a product's life cycle (Garnett et al., 2016). The system boundaries of LCAs can differ, with the most comprehensive boundaries being "cradle to grave." While the systems boundaries varied by study, nearly all began with the "cradle" or the raw materials needed for agricultural inputs. Many studies stopped short of undertaking a full life cycle analysis through the "grave" or the end point where a final product is disposed; instead, limiting systems boundaries to production stages such as "cradle to farm gate" or "cradle to retail." Input-output analysis was used in five studies to estimate the environmental or economic impacts of diets. Input-output analysis is an economic technique used to trace economic activity through complex supply-chain networks and estimate immediate and indirect impacts of systemic shocks (Boylan et al., 2020). Environmental data came largely from LCA databases, LCA studies, previously published peer-review literature, national environmental or agricultural database such as those maintained by ministries of agriculture, and global databases, for example the Water Footprint Network.

Sociocultural data relied largely on household consumption and expenditure surveys, cost of living surveys, market research data from sources like Kantar world panel purchase database (Consumer Panels, 2021), and price audits of local food environments. Other sociocultural data came from study-specific surveys on attitudes and practices or taste preferences, or were derived from food consumption surveys.

Concepts and Indicators of Sustainable Healthy Diets

Forty-two percent of articles in our review assessed the sustainability of diets using both health and environmental indicators. Relatively few articles (32%) assessed the sustainability of diets using any sociocultural indicators. Less than 25% of the articles assessed the sustainability of diets across all three aspects (**Figure 4**).

Health Concepts and Indicators

Seventy-five articles (72% of the sample) assessed the health aspects of diets. A total of 143 health indicators were identified within these articles, including 82 unique health indicators (**Supplementary Table 5**). Indicators were coded to concepts related to diet quality, diet quantity, and health outcomes.

While no universal definition for diet quality exists, the concept of diet quality is frequently examined through parameters such as nutrient adequacy, variety or diversity, moderation, nutrient density, and food safety (Alkerwi, 2014). Adequacy refers to the attainment of dietary energy, macro-, and micronutrients appropriate to age, sex, disease status, and physical activity level for a healthy life. Adequacy was one

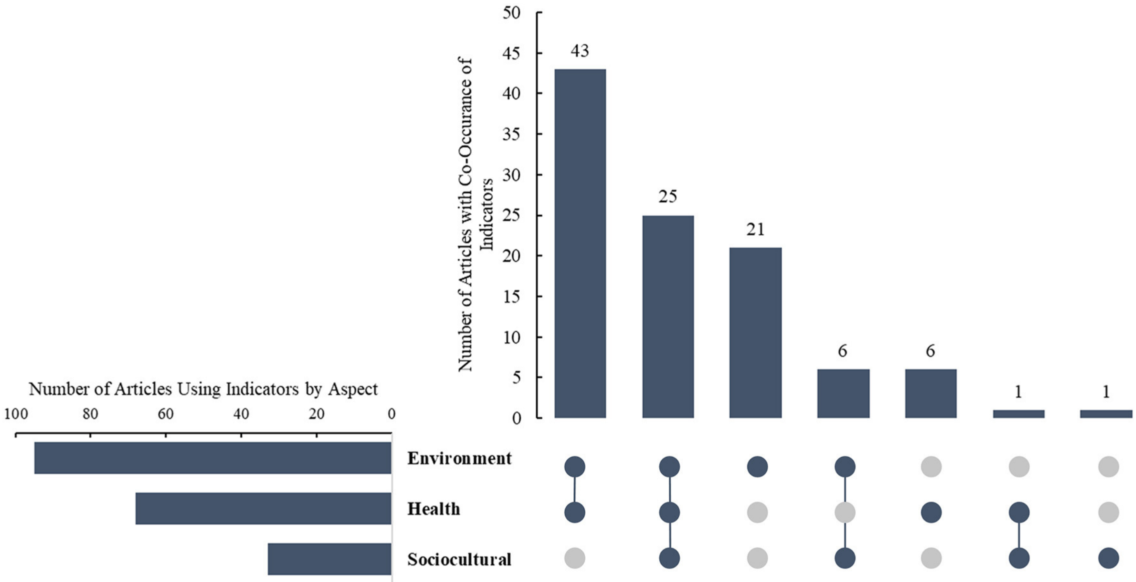


FIGURE 4 | UpSet plot of articles using indicators to assess the sustainability of diets across three aspects. The left bar plot represents the total number of articles using health or nutrition, environmental, sociocultural, or economic indicators. Every possible intersection is represented by the bottom plot, and their occurrence is shown in the top bar plot.

of the more frequently assessed health concepts ($n = 22$; 15% of the health indicators) and was often measured through indicators that determined adequate total energy, macronutrient, and micronutrient intake based on national and international recommendations (**Table 1**). Nutrient density reflects the nutrient content of a given food relative to its total energy content. Approximately 11% ($n = 16$) of the health indicators measured nutrient density, with the Nutrient Rich Food Index and the Nutrient Rich Diet Index (Fulgoni et al., 2009; Van Kernebeek et al., 2014) being the most frequently used. Moderation refers to avoiding or limiting foods that contribute to an excess risk to disease. Of the indicators used to assess moderation ($n = 12$; 8% of the health indicators), most focused on the total amount or proportion of animal source foods or animal source protein in the diet. Diversity reflects the consumption of a variety of foods across and within food groups over a given period of time. The concept of diversity was assessed through indicators such as the Diet Diversity Score, the Minimum Dietary Diversity indicator for young children, and the Functional Diversity score (Steyn et al., 2006; Luckett et al., 2015; WHO., 2021). Food safety is another parameter of diet quality and includes both foodborne disease and harmful hazards such as toxins and food contaminants. Food safety was found only once in our review of indicators. The concept of diet quality was most frequently assessed through composite indicators, which measured multiple concepts of diet quality previously mentioned (e.g., adequacy, moderation, diversity, etc.) ($n = 47$; 33% of the health indicators). Of the indicators which assessed multiple concepts of diet quality, the most frequently used indicators where healthy eating indices based on national dietary guidelines (e.g., Brazilian Healthy Eating Index, the DHD15-Index, and the Healthy Eating Index), Mediterranean Diet Scores, and the PANDiet score (Trichopoulou et al., 2005; Guenther et al., 2008; Previdelli et al., 2011; Verger et al., 2012; Naja et al., 2015; Looman et al., 2017). Other frequently used indicators included total energy and macronutrient intake and measures of adequacy (such as total energy, macronutrient, micronutrient, fruit and vegetable intake, etc.) based on national or international recommendations (both nutrient- and food-based).

Other health indicators related to concepts of diet quantity and health outcomes. Diet quantity is a concept referring to the total dietary energy supply or intake. Diet quantity was rarely assessed ($n = 4$; 3% of health indicators), but when it was, it focused on energy supply or availability and energy intake. Finally, health outcomes were the second most frequently assessed health concept ($n = 26$; 18% of health indicators). Nearly all health outcomes were morbidity or mortality indicators for chronic diseases such as coronary heart disease, stroke, type 2 diabetes, and certain cancers. The most frequently used health outcome indicators were Disability Adjusted Life Years (DALYs) from cardiovascular disease, diabetes, and/or cancer. Other health-related indicators included prevalence of underweight and stunting for children <5 years of age, avoided premature deaths, reduced DALYs, years of life saved, and Health Gain Score (Van Dooren et al., 2014).

Strengths and Limitations of Health and Nutrition Indicators

The authors of the included articles reported several strengths and limitations of different health indicators. In the case of nutrient adequacy, indicators were frequently justified by researchers because they were based on national or international guidelines for optimal nutrient intake (Tyszler et al., 2016; Kramer et al., 2017; Lachat et al., 2018; Rao et al., 2018), however, some articles noted that bioavailability of nutrients may not have been considered (de Ruiter et al., 2018) and even when taken into account, bioavailability can vary substantially with other individual- and household-level factors (Rao et al., 2018). Indicators of nutrient density, such as the Nutrient Rich Food Index, were selected because they had been shown to track diet quality more effectively compared with other indices and because they had been validated in prior studies (Castañé and Antón, 2017; González-García et al., 2018). A noted strength of the Nutrient Rich Diet Index was that because it is not scaled to energy intake, it allows for comparison between diets with different caloric content, therefore, easing the comparisons across the literature (Esteve-Llorens et al., 2020). While indices like the Nutrient Rich Diet Index have been validated, one study noted that nutrient density scores are less "transparent" making results highly dependent on how the score is constructed and may be difficult to interpret (Röös et al., 2015). Diet diversity indicators among children were justified as proxy indicators of diet quality associated with nutrient adequacy of children's diets and based on prior validation studies among children in the article's age range (Galway et al., 2018). Among indicators for multiple components of diet quality, the PANDiet score was justified because it is based on adherence to national nutrition and health recommendations and tracts with other indicators of nutritional quality among French and U.S. national health and nutrition surveys (Masset et al., 2014b; Lacour et al., 2018; Seconda et al., 2018, 2019). The DHD15-Index, an example of one specific healthy eating index used, was justified because it reflects adherence to the Dutch food-based dietary guidelines and is also a measure of health since it is negatively correlated with mortality and cardiometabolic risk factors (Van Dooren et al., 2018b; Vellinga et al., 2019). Similar to the DHD15-Index, other composite indices such as healthy eating indices, the Health Score, and the Diet Quality Index were justified because they were based on national dietary guidelines (Carvalho et al., 2013; Wrieden et al., 2019) and assessed overall diets beyond single nutrients (Rose et al., 2019), an important factor for the reduction of obesity and diet-related non-communicable diseases (Van Dooren et al., 2014).

Environmental Concepts and Indicators

Ninety-five articles (92% of the sample) assessed the sustainability of diets using environmental indicators. A total of 262 environmental indicators were identified within these articles, including 117 unique environmental indicators (**Supplementary Table 5**). Indicators were coded to concepts related to natural resources (e.g., water use, land use, biodiversity, etc.) and climate change (e.g., greenhouse gases, ozone depletion, etc.)

Indicators related to greenhouse gases were the most frequently utilized out of all the environmental concepts ($n = 77$; 29% of environmental indicators) (**Table 2**). Greenhouse gases includes gases such as carbon dioxide, methane, and nitrous oxide, which lead to global warming. The most frequently used indicators related to greenhouse gases included GHGEs, carbon footprint, and global warming potential. Water use was the second most frequently assessed environmental concept of diets ($n = 47$; 18% of environmental indicators). Water use quantifies the amount of water used to produce various goods and services. Frequently used indicators of water use included total water use and water footprint, blue water use and blue water footprint, green water use and green water footprint, freshwater use, and water scarcity footprint. Land use was another frequently assessed environmental concept for diets ($n = 36$; 14% of environmental indicators) that refers to the designated use of land by humans such as cropland, grazeland, and forest management. Commonly used indicators for assessing land use included total land use, land occupation, cropland use, ecological footprint, and nature occupation. Energy use ($n = 16$; 6% of environmental indicators) was frequently assessed through total energy use, energy consumption, cumulative energy demand, and non-renewable energy. Toxicology refers to the assessment of toxic substances in the environment and was frequently assessed through indicators such as ecotoxicity, human toxicity, particulate matter-related emissions, and respiratory inorganics ($n = 16$; 6% of environmental indicators). Eutrophication refer to excess levels of nutrients (e.g., nitrogen and phosphorus) in a body of water, while acidification refers to excess acid in the soil, water, or air. Frequent indicators for eutrophication included eutrophication potential, freshwater eutrophication, and marine eutrophication. Acidification was most often assessed through acidification potential and air acidification. Reactive nitrogen includes all the biological, chemical, and radiative active nitrogen compounds in the atmosphere. Nitrogen application and nitrogen footprint were the most frequently used indicators for assessing reactive nitrogen. Ozone depletion refers to a decline in the level of ozone gas as a result of its breakdown into oxygen. Ozone depletion was frequently measured through indicators such as ozone layer depletion and photochemical ozone depletion. Biodiversity refers to the variety and variability of living organisms in a given area. Biodiversity was most commonly assessed through species loss from land use followed by biodiversity damage potential and extinction rate. Indicators for food waste and phosphorus use, while infrequent, were leveraged in a few articles. Other common indicators include those that combined multiple environmental concepts such as the ReCiPe score (Huijbregts et al., 2017) which can include up to 18 environmental indicators. Other composite environmental indicators included the GHGE-Land Use score and sustainability scores (Van Dooren et al., 2014; van Dooren and Aiking, 2016; Fresán et al., 2018).

Strengths and Limitations of Environmental Indicators

The authors noted several strengths and limitations of environmental indicators in the included articles. Regarding greenhouse gases, authors frequently noted that GHGE can be used as a proxy for other environmental impacts since it is often highly-correlated with other phenomenon such as eutrophication, acidification, land use, and other environmental indicators (Masset et al., 2014b, 2015; Van de Kamp and Temme, 2018; Van de Kamp et al., 2018; Van Dooren et al., 2018b). Conversely, other articles which employed GHGE noted that other environmental indicators such as biodiversity loss and water use are important environmental impacts that still need to be taken into account (Masset et al., 2014b; Arrieta and González, 2018), thus suggesting that GHGE alone is insufficiently capture environmental impact. Carbon footprint was often justified due to its widespread use in studies on dietary patterns (Lukas et al., 2016; Esteve-Llorens et al., 2019b, 2020). However, some articles noted the selected systems boundaries (e.g., cradle-to-gate, cradle-to-store, cradle-to-grave) can significantly impact carbon footprint estimates (Esteve-Llorens et al., 2019a, 2020). The strengths and limitations of water use varied considerably depending on the type of water use assessed. The efficient use of green water can decrease reliance on blue water and the inclusion of green water in water resource management is now frequently recommended (Vanham et al., 2016; Kim et al., 2020). One article noted that water footprint, when used only in its aggregate form (summed total of blue, green, and gray water), can be misleading due to the significant tradeoffs that exist between blue and green water, and their substantial differences from gray water. Moreover, water footprint represents only the quantity of water used without considering how it relates to environmental impact (De Laurentiis et al., 2019). Water scarcity footprint was a preferred indicator in some articles because it considers the different impacts water use has according to a particular region (Hess et al., 2015; De Laurentiis et al., 2019; Ridoutt et al., 2019). A number of strengths were also mentioned with regard to combined environmental indicators. Because GHGE are one of the most commonly accepted indicators for assessing environmental impacts of dietary patterns and because land use and changes in land use are good proxies for biodiversity, the GHGE-Land Use score was considered a strong indicator by one article (van Dooren and Aiking, 2016). Similarly, a sustainability score derived from GHGE and land use, was justified in another article because the score incorporated the two most important contributors to environmental impacts of agricultural production (GHGE and land use), along with fossil fuels (Van Dooren et al., 2014). While environmental indicators like GHGE, land occupancy, and fossil energy can individually contribute to sustainability assessments, tradeoffs exist between them. The strength of using a ReCiPe or partial ReCiPe score, which includes these three indicators and up to 15 others, is that it avoids the potentially undesirable negative effect of assessing one indicator alone (Kramer et al., 2017).

Sociocultural Concepts and Indicators

Thirty-three articles (32% of the sample) assessed the sustainability of diets using sociocultural indicators. A total of 59 sociocultural indicators were identified within these articles, including 43 unique sociocultural indicators (**Supplementary Table 5**). Indicators were coded to concepts related to cultural acceptability, meal satisfaction, animal welfare, and economic costs.

The main sociocultural concepts measured were the cost of diets ($n = 24$; 41% of sociocultural indicators), cultural acceptability ($n = 10$; 17% of sociocultural indicators), and environmental costs ($n = 7$; 12% of sociocultural indicators) (**Table 3**). Of the 24 indicators related to costs of diets, most focused on the total cost of diets, cost of meals, cost of recipes, or cost of nutrients. Four indicators focused on the affordability of diets, such as the share of household budget dedicated to purchasing food or the ratio of food expenditure to per capita income. Cultural acceptability was most frequently measured as a minimal departure from the current diet. Indicators of environmental costs included cost benefits related to environmental improvements, the cost of total environmental impact of diets, and the cost of GHGE, total energy, and total water embodied in food consumption. Other concepts measured included animal welfare, satisfaction, and health costs. Animal welfare was assessed using animal life years suffered, loss of animal lives, and loss of morally adjusted animal lives. Satisfaction was measured through the appreciation of meals, palatability (based on food portions, frequency and associations), and tastiness of meals. Of the four indicators of health costs, two assessed health savings costs (cost-benefit due to health improvements and cost per DALYs saved) and the other two assessed health costs attributed to obesity.

Strengths and Limitations of Sociocultural Indicators

Relatively few strengths or limitations were cited concerning the sociocultural indicators used for assessing the sustainability of diets. Cultural acceptability of diets was not directly measured but assumed to exist in seven articles because the study designs attempted to maintain close adherence to current consumption patterns and food choices (Masset et al., 2014b; Kramer et al., 2017; Gazan et al., 2018; Rao et al., 2018; Benvenuti et al., 2019; Perignon et al., 2019; Reynolds et al., 2019). A clear limitation of this approach is that it does not guarantee that dietary shifts within a certain degree of current consumption patterns would be acceptable to consumers (Perignon et al., 2019); nor does it account for other cultural and traditional factors which can strongly influence food choice (Donati et al., 2016). When it comes to determining the cost of diets, the price of foods as an indicator can be expressed as price/kg and price/kcals (Masset et al., 2014a). One article noted that this unit of expression gives significantly different results for foods high in fat, sugar, salt, and for fruits and vegetables (Masset et al., 2014a). While one article noted that attempting to assess the affordability of diets as a ratio of diet costs relative to household income was a strength (Seconda et al., 2019), another noted it may lead to approximations in diet monetary costs assessments if there is a large time gap between when food price data and dietary intake data are collected (Seconda et al., 2018).

Cross-Cutting Indicators

A total of 11 indicators were identified during the review that cut across multiple aspects of diets' sustainability (**Table 4**), including 10 unique indicators (**Supplementary Table 5**). Out of these 11 indicators, nearly all cut across just two aspects, health and environment ($n = 8$; 72% of cross-cutting indicators). These indicators included measures such as carbon footprint per nutrient score, nutrient GHGE efficiency, and nutritional water

TABLE 4 | Cross-cutting indicators measured and frequency of use in the scoping review.

Cross cutting indicators (n = 11)		
Concept	**Frequency count, *n***	**Examples**
Cross-cutting	11	Sustainability score; people nourished per hectare; nutritional water productivity; carbon footprint per nutrient score; nutrient GHGE efficiency; Nutrient Density to Climate Impact Index

productivity. Sustainability scores and the sustainability index cut across health, environment, and sociocultural aspects.

DISCUSSION

Indicators for sustainable healthy diets—when they are measurable, robust, and verifiable—can provide critical information for policy makers, researchers, civil society, and industry. While the exact composition of diets will vary across population groups and contexts, the importance of being able to measure progress toward national or subnational targets for promoting sustainable healthy diets over time is critical.

Our review found that while 28% of the 103 articles included referred to or cited the 2010 definition for "sustainable diets," fewer than 25% of all studies measured concepts across all three aspects of sustainability (health, environment, and sociocultural aspects). This suggests that the different aspects of sustainability are rarely comprehensively acknowledged or assessed when it comes to diets. While 92% of the studies we reviewed included any environmental indicators, a much smaller proportion (32%) included any sociocultural indicators. This imbalance is consistent with other literature reviews on measures of diets' sustainability, which found ≥70% of studies focused on human and/or environmental health outcomes and ≤30% focused on sociocultural or economic outcomes (Jones et al., 2016; Eme et al., 2019). Indicators for the sociocultural aspects of sustainability have been either under-researched or poorly established (Meybeck and Gitz, 2017). This is likely due to the fact that defining concepts and measurements within this aspect of sustainability is particularly challenging (Comerford et al., 2020).

Our review found a disproportional amount of research on the environmental and health aspects of diets, as well as the high degree of heterogeneity in indicators used across studies examining these two aspects. The breadth of indicators currently in use across research on the sustainability of diets was also consistent with the findings of recent literature reviews (Jones et al., 2016; Eme et al., 2019). This was particularly true for the diet quality concepts for which 55 unique indicators were identified (**Supplementary Table 5**). Capturing all aspects of diet quality is challenging and developing valid food- and diet-related measures of diet quality remains difficult due to the variety of dietary patterns observed globally (Alkerwi, 2014; FAO, 2020). A recent synthesis of dietary quality metrics for validating the double burden of malnutrition identified 19 dietary metrics, including 7 related to maternal and child health and 12 developed for NCDs (Miller et al., 2020). However, no metric was found to be applicable for both, and the authors expressed a need to develop novel dietary metrics for both maternal and child health and NCDs. While the authors of the review noted environmental sustainability measurements were outside the scope of their review, they highlighted the importance of incorporating environmental impacts into future dietary metrics. Another recent systematic review of diet quality metrics identified 81 different indices for diet quality (Trijsburg et al., 2019). However, only 18 were eligible for use in low- and middle-income countries and even then 16 indices failed to capture three important dimensions of diet quality (adequacy, diversity, and moderation) and the other two were country-specific. The authors emphasized the urgent need to develop both country-specific indices based on food-based dietary guidelines as well as a global diet quality index in order to allow cross-country comparisons.

While most research on the environmental effects of diets has been conducted on a small number of concepts—particularly greenhouse gases, land use, and water use—measures for eutrophication, acidification, nitrogen and phosphorus use, biodiversity, etc. are also being used. A recent literature review examined 55 different indicators for assessing the environmental impacts of diets (Van Dooren et al., 2018a). Through a selection process, the researchers concluded that two of these indicators (GHGE and land use) fulfilled most criteria necessary for addressing the environmental impact of diets. Many articles have highlighted the tradeoffs or synergies that exist across different environmental indicators (Kramer et al., 2017; Kim et al., 2020). Similar to nutritional indicators, environmental indicators are not always positively correlated; gains made through dietary changes in one indicator (such as GHGE) do not guarantee gains in other indicators (such as water use). Even within the same concept, such as water use, tradeoffs can still exist. For example, a recent systematic review on water footprints of diets underscored the importance of distinguishing between green water and blue water in addition to measuring total water footprint (Harris et al., 2020). The authors found considerable differences in blue and green water footprint of diets depending on geography, with blue water footprints being particularly high in Asia, suggesting that changes in diets alone may be insufficient to reduce these strains (Harris et al., 2020). No such constraints would have been identified had the authors examined aggregate total water footprints alone.

The breadth of indicators currently in use for measuring the different aspects of diets' sustainability may create challenges for researchers, evaluators, and policy makers to identify and select the most appropriate measures. Furthermore, the lack of common measures makes the comparison of study results across time and place difficult. This is an important consideration for monitoring progress at a national or subnational level or analyzing trends over time. The selection of indicators can be a complex and time-consuming process. It often involves an examination of the quality of proposed indicators and a process of engaging stakeholders in their selection. The criteria

TABLE 5 | Examples of criteria used for selecting sustainable healthy diet indicators (CIHEAM/FAO, 2015; Mason and Lang, 2017; Mayton et al., 2020).

Indicator selection criteria	Issue addressed
Ability to provide effective feedback to decision-makers (Mason and Lang, 2017)	Is the indicator useful for policy or program improvement efforts?
Acceptability to actors and stakeholder (Mason and Lang, 2017; Mayton et al., 2020)	Is the indicator collectively valued by all stakeholders?
Alignment with national policy priorities (Mayton et al., 2020)	Does the indicator align with national priorities for health and sustainability?
Creditability with experts (Mason and Lang, 2017)	Is the indicator deemed to be scientifically sound by subject matter experts?
Data accessibility (Mason and Lang, 2017; Mayton et al., 2020)	Is the indicator based on data that is publically available or data that could be accessed with reasonable cost-benefit ratio?
Disaggregatability or the ability to expand into details or finer scale (Mason and Lang, 2017)	Can the indicator be broken down into areas of particular interest, such as population subgroups or regional areas?
Ease of interpretation (CIHEAM/FAO, 2015)	Is the direction that the indicator should develop for improved sustainability clear?
Measurability (Mason and Lang, 2017)	Can the indicator be counted, observed, analyzed, tested, or otherwise measured?
Monitorability (CIHEAM/FAO, 2015; Mason and Lang, 2017)	Is the indicator based on data that is readily available or data that could be made readily available at a reasonable cost—benefit ratio?
	Is the indicator's data source updated within the needed time periods?
Relevance to the question being asked (CIHEAM/FAO, 2015; Mason and Lang, 2017)	Is the indicator the best measure currently available to answer the question?
Reliability (CIHEAM/FAO, 2015)	Are the indicator's underlying data collection and analysis methods consistent across time and place?
Representativeness (CIHEAM/FAO, 2015)	Can the indicator be taken to represent trends within a current population group or geography?
Sensitivity/responsiveness to change over time (Mason and Lang, 2017)	Does the indicator act as an early warning system while there is still time to prevent negative consequences?
Understandability (CIHEAM/FAO, 2015; Mason and Lang, 2017)	Is the indicator clear, simple, and unambiguous?
Validity (Mason and Lang, 2017)	Is the indicator an accurate reflection of the concept it intends to measure?

used to select indicators can (1) aid in the establishment of a shared process and vocabulary for stakeholders to select indicators, (2) reinforce the linkage between the indicators and the evaluation or research questions being addressed, and (3) help in the design, collection, storage, and retrieval of data that are clearly linked to the intended uses of findings (MacDonald, 2013). Selecting indicators for measuring the different aspects of diets' sustainability should rely on pre-defined criteria such as those listed in **Table 5**. However, this table does not reflect an exhaustive list of criteria that could be drawn from for selecting indicators. As with the selection of any indicator, there are always tradeoffs between completeness and simplicity.

If sustainable healthy diets are to be achieved, we must accelerate progress to coordinate research and collaboratively build the evidence-based needed to address diets' unsustainability. Researchers, evaluators, and policy makers need decision-support tools to aid them in selecting indicators that are most appropriate for measuring different aspects of diets' sustainability from the large number that are currently being used in research and practice. These basic tools would enhance investigators' capacity to evaluate the growing number of simulated and natural experiments aimed at promoting sustainable healthy diets by supporting the use of common measures for systematic analyses and comparisons across different studies. FAO is currently working on plans to develop one such tool—a compendium of indicators for sustainable healthy diets—based on the findings of this scoping review and input from technical experts. Additionally, measures registries, such as the one developed through the National Collaboration on Childhood Obesity Research (NCCOR) in the United States, may provide a blueprint for such a decision-support resource (National Collaborative on Childhood Obesity Research, 2020). Given the complexity of measuring the sustainability of diets, including the diversity of indicators and data sources that are drawn from, it may be beneficial to draw lessons from the development of other measures registries, surveillance catalogs, and user guides.

Limitations

Our scoping review had several limitations. First, the literature databases and the key word search strings used likely limited our results. Given the complexity of the concept of sustainability in its application to diets, there is often inconsistency in the terminology used to describe work in this area. It was beyond the time and resources of our project to carry out individual scoping reviews for each aspect of sustainability (e.g., economically sustainable diets); therefore we were parsimonious in our key word search string. Despite this limitation, our results are comparable to the findings of two recent literature reviews, even with differences in the key words and databases searched (Jones et al., 2016; Eme et al., 2019). Secondly, our exclusion criteria likely excluded some articles that contained indicators relevant to assessing diets' sustainability, such as studies focused on individual food items or food groups. While studies focusing on individual foods or food groups could be relevant to the aims of this review, many of the databases used for evaluating environmental impacts of population-, household-, or individual-level diets relied on databases, such as the EcoInvent life cycle inventory database, which have been constructed using studies on individual food items. Third, a clear geographical imbalance continues to be a limitation of the current literature. The vast majority (>70%) of studies included in our review focused on high-income countries, particularly western, northern, and southern Europe. Many of the data sources drawn from, such as national health and nutrition surveys, household consumption and expenditure surveys, or LCA databases, are not available in many low- and middle-income countries. Therefore, the indicators generated in these studies might not be applicable to low-resource contexts. This geographical bias also overlooks things like the burden of diseases and dietary patterns that tend to characterize low- and middle-income countries. Our review identified relatively few health outcome indicators for other forms of malnutrition apart from those for diet-related NCDs. Finally, while a concerted effort was made to map indicators with their corresponding aspects, not all indicators discretely fit into one domain. For example, we categorized indicators for food waste as measures of the environmental aspect of sustainable healthy diets. However, food waste indicators could also illustrate phenomena related to food safety (health aspect), social norms and consumer attitudes, or even economic constraints (sociocultural aspect). While this review aimed to describe the range of indicators currently used, during the indicator selection process it is worth considering that one indicator may partially describe many different concepts or aspects of sustainability.

CONCLUSION

Quantifiable indicators for sustainable healthy diets are critical to understanding current trends, setting targets, and monitoring progress across national and sub-national levels. Our review adds to the current body of knowledge by describing the reported strengths and limitations of frequently used indicators and how sustainable healthy diets were defined by researchers. Serious barriers to accelerating progress toward sustainable healthy diets includes the persistent geographical imbalance in research on sustainable healthy diets, the tendency to overlook sociocultural aspects of sustainable healthy diets, and the lack of common definitions and metrics used in research. Each of these barriers must be addressed in order for sustainable healthy diets to be realized. Weighing the quality of evidence and critical examination of the indicator quality was outside the scope of this review, but is the next critical step toward aiding researchers, evaluators, and policy makers in selecting appropriate indicators. Many factors have to be considered when selecting indicators for measuring diets' sustainability—including tradeoffs between and within different aspects of sustainability. These tradeoffs will require value-based decision-making that will be context specific. FAO is committed to accelerating progress on achieving sustainable healthy diets by coordinating research and collaboratively building an evidence base. Central to this commitment is the urgent need for decision-support tools to support the selection and adoption of high-performing and comparable measures across all aspects of sustainability are needed for advancing research, practice, and policy related to sustainable food systems transformation.

AUTHOR CONTRIBUTIONS

MH, GP, TB, MB-T, DQ, and FH wrote and contributed to the preparation of this manuscript. MH, GP, and FH formulated research questions explored in this review. MH, GP, DQ, and FH developed the database search string. MH, GP, and TB contributed to article screening and data extraction. MH led the analysis of the extracted data with support from MB-T, TB, and GP. All authors reviewed and contributed to the final version of the manuscript.

FUNDING

This work contributes to the Sustainable Diets in the Context of Sustainable Food Systems initiative of the One Planet Sustainable Food Systems Programme and was supported financially by the Swiss Government through a project signed with the Food and Agriculture Organization of the United Nations.

ACKNOWLEDGMENTS

We are appreciative of the contributions of Bridget Holmes, Anne Kepple, and Nancy Aburto toward the preparation of this manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.822263/full#supplementary-material

REFERENCES

Abarca-Gómez, L., Abdeen, Z. A., Hamid, Z. A., Abu-Rmeileh, N. M., Acosta-Cazares, B., and Acuin, C. (2017). Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults. *Lancet.* 390, 2627–42. doi: 10.1016/S0140-6736(17)32129-3

Adair, L. S., Fall, C. H., Osmond, C., Stein, A. D., Martorell, R., and Ramirez-Zea, M. (2013). Associations of linear growth and relative weight gain during early life with adult health and human capital in countries of low and middle income: findings from five birth cohort studies. *Lancet.* 382, 525–34. doi: 10.1016/S0140-6736(13)60103-8

Afshin, A., Sur, P. J., Fay, K. A., Cornaby, L., Ferrara, G., and Salama, J. S. (2019). Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet.* 393, 1958–72. doi: 10.1016/S0140-6736(19)30041-8

Alkerwi, A. (2014). Diet quality concept. *Nutrition.* 30, 613–8. doi: 10.1016/j.nut.2013.10.001

Arrieta, E. M., and González, A. D. (2018). Impact of current, National Dietary Guidelines and alternative diets on greenhouse gas emissions in Argentina. *Food Policy.* 79, 58–66. doi: 10.1016/j.foodpol.2018.05.003

Bacha, F., and Gidding, S. S. (2016). Cardiac abnormalities in youth with obesity and type 2 diabetes. *Curr. Diab. Rep.* 16:62. doi: 10.1007/s11892-016-0750-6

Benvenuti, L., Santis, D., Di Sero, A., Franco, A., and Concurrent, N. (2019). Economic and environmental impacts of food consumption: are low emissions diets affordable? *J. Cleaner Prod.* 236:117645. doi: 10.1016/j.jclepro.2019.117645

Black, R. E., Victora, C. G., Walker, S. P., Bhutta, Z. A., Christian, P., De Onis, M., et al. (2013). Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet.* 382, 427–51. doi: 10.1016/S0140-6736(13)60937-X

Boylan, S. M., Thow, A. M., Tyedmers, E. K., Malik, A., Salem, J., and Alders, R. (2020). Using input-output analysis to measure healthy, sustainable food systems. *Front. Sustain. Food Syst.* 4:93. doi: 10.3389/fsufs.2020.00093

Burlingame, B., and Dernini, S. (2012). *Sustainable Diets and Biodiversity Directions and Solutions for Policy, Research and Action*. Rome: FAO Headquarters.

Carvalho, D. E., César, A. M., Fisberg, C. L., Marchioni, R. M., and Excessive, D. M. (2013). meat consumption in Brazil: diet quality and environmental impacts. *Public Health Nutr.* 16, 1893–9. doi: 10.1017/S1368980012003916

Castañé, S., and Antón, A. (2017). Assessment of the nutritional quality and environmental impact of two food diets: a Mediterranean and a vegan diet. *J. Clean Prod.* 167, 929–37. doi: 10.1016/j.jclepro.2017.04.121

CIHEAM/FAO. (2015). *Mediterranean Food Consumption Patterns: Diet, Environment, Society, Economy and Health*. Rome: CIHEAM/FAO.

Cloete, P. C., and Idsardi, E. F. (2013). Consumption of indigenous and traditional food crops: perceptions and realities from South Africa. *Agroecol. Sustain. Food Syst.* 37, 902–14. doi: 10.1080/21683565.2013.805179

Comerford, K., Arndt, C., Drewnowski, A., Ericksen, P., Griffin, T., and Hendrickson, M. (2020). Proceedings of a workshop on characterizing and defining the social and economic domains of sustainable diets. *Sustainability.* 12:4163. doi: 10.3390/su12104163

Consumer Panels (2021). *Kantar Worldpanel*. https://www.kantarworldpanel.com/global/Consumer-Panels (accessed April 7, 2021).

Cote, A. T., Harris, K. C., Panagiotopoulos, C., Sandor, G. G., and Devlin, A. M. (2013). Childhood obesity and cardiovascular dysfunction. *J. Am. Coll. Cardiol.* 62, 1309–19. doi: 10.1016/j.jacc.2013.07.042

De Laurentiis, V., Hunt, D. V., Lee, S. E., and Rogers, C. D. (2019). EATS. A life cycle-based decision support tool for local authorities and school caterers. *Int. J. Life Cycle Assess.* 24, 1222–38. doi: 10.1007/s11367-018-1460-x

de Ruiter, H., Macdiarmid, J. I., Matthews, R. B., and Smith, P. (2018). Moving beyond calories and protein: micronutrient assessment of UK diets and land use. *Glob. Environ. Change.* 52, 108–16. doi: 10.1016/j.gloenvcha.2018.06.007

Di Bonito, P., Del Giudice, E. M., Chiesa, C., Licenziati, M. R., Manco, M., Franco, F., et al. (2018). Preclinical signs of liver and cardiac damage in youth with metabolically healthy obese phenotype. *Nutr. Metab. Cardiovasc. Dis.* 28, 1230–6. doi: 10.1016/j.numecd.2018.08.007

Diaz, R. J., and Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science.* 321, 926–9. doi: 10.1126/science.1156401

Donati, M., Menozzi, D., Zighetti, C., Rosi, A., Zinetti, A., and Scazzina, F. (2016). Towards a sustainable diet combining economic, environmental and nutritional objectives. *Appetite.* 106, 48–57. doi: 10.1016/j.appet.2016.02.151

Downs, S. M., Payne, A., and Fanzo, J. (2017). The development and application of a sustainable diets framework for policy analysis: a case study of Nepal. *Food Policy.* 70, 40–9. doi: 10.1016/j.foodpol.2017.05.005

Eme, P. E., Douwes, J., Kim, N., Foliaki, S., and Burlingame, B. (2019). Review of methodologies for assessing sustainable diets and potential for development of harmonised indicators. *Int. J. Environ. Res. Public Health.* 16:E1184. doi: 10.3390/ijerph16071184

Esteve-Llorens, X., Darriba, C., Moreira, M. T., Feijoo, G., and González-García, S. (2019a). Towards an environmentally sustainable and healthy Atlantic dietary pattern: life cycle carbon footprint and nutritional quality. *Sci. Total Environ.* 646, 704–15. doi: 10.1016/j.scitotenv.2018.07.264

Esteve-Llorens, X., Martin-Gamboa, M., Iribarren, D., Moreira, M. T., Feijoo, G., and Gonzalez-Garcia, S. (2020). Efficiency assessment of diets in the Spanish regions: a multi-criteria cross-cutting approach. *J. Clean Prod.* 242:118491. doi: 10.1016/j.jclepro.2019.118491

Esteve-Llorens, X., Moreira, M. T., Feijoo, G., and González-García, S. (2019b). Linking environmental sustainability and nutritional quality of the Atlantic diet recommendations and real consumption habits in Galicia (NW Spain). *Sci. Total Environ.* 683, 71–9. doi: 10.1016/j.scitotenv.2019.05.200

FAO, IFAD, UNICEF, WFP, and WHO. (2020). *The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets*. Rome: FAO.

FAO and WHO. (2019). *Sustainable Healthy Diets—Guiding Principles*. Rome: FAO and WHO.

FAO. (2011). *Global Food Losses and Food Waste—Extent, Causes and Prevention*. Rome: FAO.

Fieldhouse, P. (2013). *Food and Nutrition: Customs and Culture*. New York: Springer.

Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan, G., and Carpenter, S. R. (2005). Global consequences of land use. *Science.* 309, 570–4. doi: 10.1126/science.1111772

Fresán, U., Martínez-Gonzalez, M. A., Sabaté, J., and Bes-Rastrollo, M. (2018). The Mediterranean diet, an environmentally friendly option: evidence from the Seguimiento Universidad de Navarra (SUN) cohort. *Public Health Nutr.* 21, 1573–82. doi: 10.1017/S1368980017003986

Fulgoni, V. L., Keast, D. R., and Drewnowski, A. (2009). Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods. *J Nutr.* 139, 1549–54. doi: 10.3945/jn.108.101360

Galway, L. P., Acharya, Y., and Jones, A. D. (2018). Deforestation and child diet diversity: a geospatial analysis of 15 Sub-Saharan African countries. *Health Place.* 51, 78–88. doi: 10.1016/j.healthplace.2018.03.002

Garnett, T., Röös, E., Nicholson, W., and Finch, J. (2016). *Environmental Impacts of Food: An Introduction to LCA*. Oxford: University of Oxford, Food Climate Research Network.

Gazan, R., Barré, T., Perignon, M., Maillot, M., Darmon, N., and Vieux, F. (2018). methodology to compile food metrics related to diet sustainability into a single food database: application to the French case. *Food Chem.* 238, 125–33. doi: 10.1016/j.foodchem.2016.11.083

González-García, S., Esteve-Llorens, X., Moreira, M. T., and Feijoo, G. (2018). Carbon footprint and nutritional quality of different human dietary choices. *Sci. Total Environ.* 644, 77–94. doi: 10.1016/j.scitotenv.2018.06.339

Guenther, P. M., Reedy, J., and Krebs-Smith, S. M. (2008). Development of the healthy eating index-2005. *J. Am. Diet Assoc.* 108, 1896–901. doi: 10.1016/j.jada.2008.08.016

Guh, D. P., Zhang, W., Bansback, N., Amarsi, Z., Birmingham, C. L., and Anis, A. H. (2009). The incidence of co-morbidities related to obesity and overweight: a systematic review and meta-analysis. *BMC Public Health.* 9:88. doi: 10.1186/1471-2458-9-88

Gussow, J. D., and Clancy, K. L. (1986). Dietary guidelines for sustainability. *J. Nutr. Educ.* 18, 1–5. doi: 10.1016/S0022-3182(86)80255-2

Gustafson, D., Gutman, A., Leet, W., Drewnowski, A., Fanzo, J., and Ingram, J. (2016). Seven food system metrics of sustainable nutrition security. *Sustainability.* 8:196. doi: 10.3390/su8030196

Harris, F., Moss, C., Joy, E. J. M., Quinn, R., Scheelbeek, P. F. D., and Dangour, A. D. (2020). The water footprint of diets: a global systematic review and meta-analysis. *Adv Nutr.* 11, 375–86. doi: 10.1093/advances/nmz091

Headey, D. D., and Alderman, H. H. (2019). The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. *J Nutr.* 149, 2020–33. doi: 10.1093/jn/nxz158

Hess, T., Andersson, U., Mena, C., and Williams, A. (2015). The impact of healthier dietary scenarios on the global blue water scarcity footprint of food consumption in the UK. *Food Policy.* 50, 1–10. doi: 10.1016/j.foodpol.2014.10.013

HLPE. (2017). *Nutrition and Food Systems. A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security*. Rome: HLPE.

Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., and Vieira, M. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess.* 22, 138–47. doi: 10.1007/s11367-016-1246-y

Johnston, J. L., Fanzo, J. C., and Cogill, B. (2014). Understanding sustainable diets: a descriptive analysis of the determinants and processes that influence diets and their impact on health, food security, and environmental sustainability. *Adv. Nutr.* 5, 418–29. doi: 10.3945/an.113.005553

Jones, A. D., Hoey, L., Blesh, J., Miller, L., Green, A., and Shapiro, L. F. (2016). Systematic review of the measurement of sustainable diets. *Adv. Nutr.* 7, 641–64. doi: 10.3945/an.115.011015

Kim, B. F., Santo, R. E., Scatterday, A. P., Fry, J. P., Synk, C. M., and Cebron, S. R. (2020). Country-specific dietary shifts to mitigate climate and water crises. *Glob. Environ. Change.* 62:101926. doi: 10.1016/j.gloenvcha.2019.05.010

Kramer, G. F., Tyszler, M., Veer, P. V., and Blonk, H. (2017). Decreasing the overall environmental impact of the Dutch diet: how to find healthy and sustainable diets with limited changes. *Public Health Nutr.* 20, 1699–709. doi: 10.1017/S1368980017000349

Lachat, C., Raneri, J. E., Smith, K. W., Kolsteren, P., Van Damme, P., and Verzelen, K. (2018). Dietary species richness as a measure of food biodiversity and nutritional quality of diets. *Proc. Natl. Acad. Sci. USA.* 115, 127–32. doi: 10.1073/pnas.1709194115

Lacour, C., Seconda, L., Allès, B., Hercberg, S., Langevin, B., and Pointereau, P. (2018). Environmental impacts of plant-based diets: how does organic food consumption contribute to environmental sustainability. *Front Nutr.* 5:8. doi: 10.3389/fnut.2018.00008

Lang, T. (2010). Crisis? What crisis? The normality of the current food crisis. *J. Agrar. Change.* 10, 87–97. doi: 10.1111/j.1471-0366.2009.00250.x

Lauby-Secretan, B., Scoccianti, C., Loomis, D., Grosse, Y., Bianchini, F., and Straif, K. (2016). Body fatness and cancer—viewpoint of the IARC Working Group. *N. Engl. J. Med.* 375, 794–8. doi: 10.1056/NEJMsr1606602

Lloyd, L. J., Langley-Evans, S. C., and McMullen, S. (2012). Childhood obesity and risk of the adult metabolic syndrome: a systematic review. *Int. J. Obes.* 36, 1–11. doi: 10.1038/ijo.2011.186

Looman, M., Feskens, E. J., de Rijk, M., Meijboom, S., Biesbroek, S., Temme, E. H., et al. (2017). Development and evaluation of the Dutch Healthy Diet index 2015. *Public Health Nutr.* 20, 2289–99. doi: 10.1017/S136898001700091X

Luckett, B. G., DeClerck, F. A., Fanzo, J., Mundorf, A. R., and Rose, D. (2015). Application of the Nutrition Functional Diversity indicator to assess food system contributions to dietary diversity and sustainable diets of Malawian households. *Public Health Nutr.* 18, 2479–87. doi: 10.1017/S136898001500169X

Lukas, M., Rohn, H., Lettenmeier, M., Liedtke, C., and Wiesen, K. (2016). The nutritional footprint–integrated methodology using environmental and health indicators to indicate potential for absolute reduction of natural resource use in the field of food and nutrition. *J. Clean Prod.* 132, 161–70. doi: 10.1016/j.jclepro.2015.02.070

MacDonald, G. (2013). *Criteria for Selection of High-Performing Indicators: A Checklist to Inform Monitoring and Evaluation*. Georgia: Centers for Disease Control and Prevention-Atlanta.

Mason, P., and Lang, T. (2017). *Sustainable Diets: How Ecological Nutrition Can Transform Consumption and the Food System*. New York: Routledge.

Mason-D'Croz, D., Bogard, J. R., Sulser, T. B., Cenacchi, N., Dunston, S., Herrero, M., et al. (2019). Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. *Lancet Planet Health.* 3:e318–29. doi: 10.1016/S2542-5196(19)30095-6

Masset, G., Soler, L. G., Vieux, F., and Darmon, N. (2014a). Identifying sustainable foods: the relationship between environmental impact, nutritional quality, and prices of foods representative of the French diet. *J. Acad. Nutr. Diet.* 114, 862–9. doi: 10.1016/j.jand.2014.02.002

Masset, G., Vieux, F., and Darmon, N. (2015). Which functional unit to identify sustainable foods. *Public Health Nutr.* 18, 2488–97. doi: 10.1017/S1368980015000579

Masset, G., Vieux, F., Verger, E. O., Soler, L. G., Touazi, D., and Darmon, N. (2014b). Reducing energy intake and energy density for a sustainable diet: a study based on self-selected diets in French adults. *Am. J. Clin. Nutr.* 99, 1460–9. doi: 10.3945/ajcn.113.077958

Mayton, H., Beal, T., Rubin, J., Sanchez, A., Heller, M., and Hoey, L. (2020). Conceptualizing sustainable diets in Vietnam: minimum metrics and potential leverage points. *Food Policy.* 91:101836. doi: 10.1016/j.foodpol.2020.101836

Meybeck, A., and Gitz, V. (2017). Sustainable diets within sustainable food systems. *Proc. Nutr. Soc.* 76, 1–11. doi: 10.1017/S0029665116000653

Miller, V., Webb, P., Micha, R., and Mozaffarian, D. (2020). Defining diet quality: a synthesis of dietary quality metrics and their validity for the double burden of malnutrition. *Lancet Planet Health.* 4, e352–70. doi: 10.1016/S2542-5196(20)30162-5

Mohanan, S., Tapp, H., McWilliams, A., and Dulin, M. (2014). Obesity and asthma: pathophysiology and implications for diagnosis and management in primary care. *Exp. Biol. Med.* 239, 1531–40. doi: 10.1177/1535370214525302

Molden, D. (editor). (2013). *Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. New York: Routledge.

Monterrosa, E. C., Frongillo, E. A., Drewnowski, A., de Pee, S., and Vandevijvere, S. (2020). Sociocultural influences on food choices and implications for sustainable healthy diets. *Food Nutr. Bull.* 41, 59S—73S. doi: 10.1177/0379572120975874

Myers, S. S., Smith, M. R., Guth, S., Golden, C. D., Vaitla, B., and Mueller, N. D. (2017). Climate change and global food systems: potential impacts on food security and undernutrition. *Annu. Rev. Public Health.* 38, 259–77. doi: 10.1146/annurev-publhealth-031816-044356

Naja, F., Hwalla, N., Itani, L., Baalbaki, S., Sibai, A., and Nasreddine, L. (2015). Novel Mediterranean diet index from Lebanon: comparison with Europe. *Eur J Nutr.* 54, 1229–43. doi: 10.1007/s00394-014-0801-1

Narang, I., and Mathew, J. L. (2012). Childhood obesity and obstructive sleep apnea. *J Nutr Metab.* 2012:134202. doi: 10.1155/2012/134202

National Collaborative on Childhood Obesity Research. (2020). *Measures Registry Resource Suite.* Available online at: https://www.nccor.org/nccor-tools/mrresourcesuite/ (accessed December 8, 2020).

Perignon, M., Sinfort, C., El Ati, J., Traissac, P., Drogue, S., and Darmon, N. (2019). How to meet nutritional recommendations and reduce diet environmental impact in the Mediterranean region? An optimization study to identify more sustainable diets in Tunisia. *Glob. Food Secur.* 23, 227–35. doi: 10.1016/j.gfs.2019.07.006

Peters, M., Godfrey, C., McInerney, P., Soares, C., Khalil, H., and Parker, D. (2015). *The Joanna Briggs Institute Reviewers' Manual 2015: Methodology for JBI Scoping Reviews*. South Australia: Joanna Briggs Institute.

Previdelli, A. N., Andrade, D. E., Pires, S. C., Ferreira, M. M., Fisberg, S. R., and Marchioni, R. M., et al. (2011). Revised version of the healthy eating index for the Brazilian Population. *Rev. Saude Pub.* 45, 794–8. doi: 10.1590/S0034-89102011000400021

Rao, N. D., Min, J., DeFries, R., Ghosh-Jerath, S., Valin, H., Fanzo, J. (2018). Healthy, affordable and climate-friendly diets in India. *Global Environ. Change.* 49, 154–65. doi: 10.1016/j.gloenvcha.2018.02.013

Reynolds, C. J., Horgan, G. W., Whybrow, S., and Macdiarmid, J. I. (2019). Healthy and sustainable diets that meet greenhouse gas emission reduction targets and are affordable for different income groups in the UK. *Public Health Nutr.* 22, 1503–17. doi: 10.1017/S1368980018003774

Ridoutt, B. G., Baird, D., Anastasiou, K., and Hendrie, G. A. (2019). Diet quality and water scarcity: evidence from a large Australian Population Health Survey. *Nutrients.* 11:E1846. doi: 10.3390/nu11081846

Röös, E., Karlsson, H., Witthöft, C., and Sundberg, C. (2015). Evaluating the sustainability of diets–combining environmental and nutritional aspects. *Environ. Sci. Policy.* 47, 157–66. doi: 10.1016/j.envsci.2014.12.001

Rose, D., Heller, M. C., Willits-Smith, A. M., and Meyer, R. J. (2019). Carbon footprint of self-selected US diets: nutritional, demographic, and behavioral correlates. *Am. J. Clin. Nutr.* 109, 526–34. doi: 10.1093/ajcn/nqy327

Sacchi, C., Marino, C., Nosarti, C., Vieno, A., Visentin, S., and Simonelli, A. (2020). Association of intrauterine growth restriction and small for gestational age status with childhood cognitive outcomes: a systematic review and meta-analysis. *JAMA Pediatr.* 174, 772–81. doi: 10.1001/jamapediatrics.2020.1097

Seconda, L., Baudry, J., Alles, B., Soler, L. G., Hercberg, S., and Langevin, B. (2018). Identification of sustainable dietary patterns by a multicriteria approach in the NutriNet-Sante cohort. *J. Clean Prod.* 196, 1256–65. doi: 10.1016/j.jclepro.2018.06.143

Seconda, L., Baudry, J., Pointereau, P., Lacour, C., Langevin, B., and Hercberg, S. (2019). Development and validation of an individual sustainable diet index in the NutriNet-Santé study cohort. *Br. J. Nutr.* 121, 1166–77. doi: 10.1017/S0007114519000369

Steyn, N. P., Nel, J. H., Nantel, G., Kennedy, G., and Labadarios, D. (2006). Food variety and dietary diversity scores in children: are they good indicators of dietary adequacy. *Public Health Nutr.* 9, 644–50. doi: 10.1079/PHN2005912

Swinburn, B. A., Kraak, V. I., Allender, S., Atkins, V. J., Baker, P. I., and Bogard, J. R. (2019). The global syndemic of obesity, undernutrition, and climate change: The Lancet Commission report. *Lancet.* 393, 791–846. doi: 10.1016/S0140-6736(18)32822-8

Tilman, D., Clark, M., Williams, D. R., Kimmel, K., Polasky, S., and Packer, C. (2017). Future threats to biodiversity and pathways to their prevention. *Nature.* 546, 73–81. doi: 10.1038/nature22900

Trichopoulou, A., Orfanos, P., Norat, T., Bueno-de-Mesquita, B., Ocké, M. C., Peeters, P. H., et al. (2005). Modified mediterranean diet and survival: EPIC-elderly prospective cohort study. *BMJ.* 330:991. doi: 10.1136/bmj.38415.644155.8F

Trijsburg, L., Talsma, E. F., De Vries, J. H., Kennedy, G., Kuijsten, A., and Brouwer, I. D. (2019). Diet quality indices for research in low- and middle-income countries: a systematic review. *Nutr. Rev.* 77, 515–40. doi: 10.1093/nutrit/nuz017

Tyszler, M., Kramer, G., and Blonk, H. (2016). Just eating healthier is not enough: studying the environmental impact of different diet scenarios for Dutch women (31–50 years old) by linear programming. *Int. J. Life Cycle Assess.* 21, 701–9. doi: 10.1007/s11367-015-0981-9

UNICEF/WHO. (2020). *The World Bank Group Joint Child Malnutrition Estimates: Levels and Trends in Child Malnutrition: Key Findings of the 2020 Edition*. Available online at: https://www.who.int/publications/i/item/jme-2020-edition (accessed September 27, 2020).

UNSD. (2020). *Methodology*. https://unstats.un.org/unsd/methodology/m49/ (accessed October 9, 2020).

Van de Kamp, M. E., and Temme, E. H. (2018). Plant-based lunch at work: effects on nutrient intake, environmental impact and tastiness—a case study. *Sustainability*. 10:227. doi: 10.3390/su10010227

Van de Kamp, M. E., van Dooren, C., Hollander, A., Geurts, M., Brink, E. J., and van Rossum, C. (2018). Healthy diets with reduced environmental impact?—The greenhouse gas emissions of various diets adhering to the Dutch food based dietary guidelines. *Food Res. Int.* 104, 14–24. doi: 10.1016/j.foodres.2017.06.006

van Dooren, C., and Aiking, H. (2016). Defining a nutritionally healthy, environmentally friendly, and culturally acceptable low lands diet. *Int. J. Life Cycle Assess.* 21, 688–700. doi: 10.1007/s11367-015-1007-3

Van Dooren, C., Aiking, H., and Vellinga, P. (2018a). In search of indicators to assess the environmental impact of diets. *Int. J. Life Cycle Assess.* 23, 1297–314. doi: 10.1007/s11367-017-1371-2

Van Dooren, C., Keuchenius, C., Vries, D. E., De Boer, J. H., and Aiking, J. H. (2018b). Unsustainable dietary habits of specific subgroups require dedicated transition strategies: evidence from the Netherlands. *Food Policy.* 79, 44–57. doi: 10.1016/j.foodpol.2018.05.002

Van Dooren, C., Marinussen, M., Blonk, H., Aiking, H., and Vellinga, P. (2014). Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns. *Food Policy.* 44, 36–46. doi: 10.1016/j.foodpol.2013.11.002

Van Kernebeek, H. R., Oosting, S. J., Feskens, E. J., Gerber, P. J., and de Boer, I. J. (2014). The effect of nutritional quality on comparing environmental impacts of human diets. *J. Clean Prod.* 73, 88–99. doi: 10.1016/j.jclepro.2013.11.028

Vanham, D., Del Pozo, S., Pekcan, A. G., Keinan-Boker, L., Trichopoulou, A., and Gawlik, B. M. (2016). Water consumption related to different diets in Mediterranean cities. *Sci Total Environ.* 573, 96–105. doi: 10.1016/j.scitotenv.2016.08.111

Vellinga, R. E., van de Kamp, M., Toxopeus, I. B., van Rossum, C., de Valk, E., and Biesbroek, S., et al. (2019). Greenhouse gas emissions and blue water use of Dutch diets and its association with health. *Sustainability.* 11:6027. doi: 10.3390/su11216027

Verger, E. O., Mariotti, F., Holmes, B. A., Paineau, D., and Huneau, J. F. (2012). Evaluation of a diet quality index based on the probability of adequate nutrient intake (PANDiet) using national French and US dietary surveys. *PLoS ONE* 7:e42155. doi: 10.1371/journal.pone.0042155

Vermeulen, S. J., Campbell, B. M., and Ingram, J. S. (2012). Climate change and food systems. *Annu. Rev. Environ. Resour.* 37, 195–222. doi: 10.1146/annurev-environ-020411-130608

WHO. (2020). *Global Health Observatory—Data Repository*. Available online at: https://apps.who.int/gho/data/view.main.NUTWHOUNDERWEIGHTv (accessed September 27, 2020).

WHO. (2021). *Indicators for Assessing Infant and Young Child Feeding Practices: Definitions and Measurement Methods*. Geneva: World Health Organization and the United Nations Children's Fund (UNICEF).

World Bank Country and Lending Groups. (2020). Available online at: http://databank.worldbank.org/data/download/site-content/CLASS.xls (accessed on October 9, 2020)

Wrieden, W., Halligan, J., Goffe, L., Barton, K., and Leinonen, I. (2019). Sustainable diets in the UK—Developing a systematic framework to assess the environmental impact, cost and nutritional quality of household food purchases. *Sustainability.* 11:4974. doi: 10.3390/su11184974

Zimmermann, M. B. (2016). The importance of adequate iodine during pregnancy and infancy. *World Rev Nutr Diet.* 115, 118–24. doi: 10.1159/000442078

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 16 December 2022
DOI 10.3389/fsufs.2022.1063419

Check for updates

OPEN ACCESS

EDITED BY
Bradley George Ridoutt,
Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

REVIEWED BY
Thierry Brunelle,
Centre de coopération internationale en recherche agronomique pour le développement, France
Kai Huang,
Beijing Forestry University, China

*CORRESPONDENCE
Nick W. Smith
n.w.smith@massey.ac.nz

SPECIALTY SECTION
This article was submitted to Nutrition and Sustainable Diets, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 07 October 2022
ACCEPTED 01 December 2022
PUBLISHED 16 December 2022

CITATION
Smith NW, Fletcher AJ, Millard P, Hill JP and McNabb WC (2022) Estimating cropland requirements for global food system scenario modeling. *Front. Sustain. Food Syst.* 6:1063419. doi: 10.3389/fsufs.2022.1063419

Estimating cropland requirements for global food system scenario modeling

Nick W. Smith[1]*, Andrew J. Fletcher[1,2], Peter Millard[3], Jeremy P. Hill[1,2] and Warren C. McNabb[1]

[1]Sustainable Nutrition Initiative®, Riddet Institute, Massey University, Palmerston North, New Zealand, [2]Fonterra Research and Development Centre, Palmerston North, New Zealand, [3]Manaaki Whenua Landcare Research, Lincoln, New Zealand

Introduction: The production of plant crops is foundational to the global food system. With the need for this system to become more sustainable while feeding an increasing global population, tools to investigate future food system scenarios can be useful to aid decision making, but are often limited to a calorie- or protein-centric view of human nutrition.

Methods: Here, a mathematical model for forecasting the future cropland requirement to produce a given quantity of crop mass is presented in conjunction with the DELTA Model®: an existing food system scenario model calculating global availability of 29 nutrients against human requirements. The model uses national crop yield data to assign yield metrics for 137 crops.

Results: The crops with the greatest variation between high and low yielding production were specific nuts, fruits, and vegetables of minor significance to global nutrient availability. The nut crop group showed the greatest overall yield variation between countries, and thus the greatest uncertainty when forecasting the cropland requirement for future increases in production. Sugar crops showed the least overall yield variation. The greatest potential for increasing global food production by improving poor yielding production was found for the most widely grown crops: maize, wheat, and rice, which were also demonstrated to be of high nutritional significance.

Discussion: The combined cropland and nutrient availability model allowed the contribution of plant production to global nutrition to be quantified, and the cropland requirement of future food production scenarios to be estimated. The unified cropland estimation and nutrient availability model presented here is an intuitive and broadly applicable tool for use in global food system scenario modeling. It should benefit future research and policy making by demonstrating the implications for human nutrition of changes to crop production, and conversely the implications for cropland requirement of food production scenarios aimed at improving nutrition.

KEYWORDS

global food system, food security, computational modeling, human nutrition, sustainability

1. Introduction

Global crop production is central to the delivery of nutrition to the world's population and will continue to be so as this population grows in the future. Insufficient future crop production risks reducing global and local food security, and increasing the burden of malnutrition. Conversely, increased crop production and the expansion of cropland poses environmental risks, including increased fertilizer, pesticide, and water use; deforestation; and loss of biodiversity (FAO, 2020b). Sustainable future cropland use will need to balance the demand for food production against the impacts of this land use.

Cropland dynamics and modeling featured at the United Nations Food Systems Summit in September 2021, with the Summit's Scientific Group emphasizing the key contribution of science through food systems modeling to support policy-makers and to avoid unintended consequences (von Braun et al., 2021). Computational modeling can be applied to global food system questions to aid thinking and decision making on future changes to achieve sustainability.

Existing models for global cropland use and production exist and have provided valuable insight into future possibilities for cropland use. For example, the Parsimonious Land Use Model (PLUM; Engström et al., 2016), has been used to identify possibilities for meeting global calorific requirements without exceeding planetary cropland boundaries (Henry et al., 2018). The GlobAgri-AgT model has been used to forecast crop and pasture area under a variety of 2050 scenarios, coupled to diet and global fore-sighting analyses (Mora et al., 2020). Other models have been used to estimate the environmental impact of forecast cropland expansion on biodiversity and carbon storage (Molotoks et al., 2018; Zabel et al., 2019).

Efforts in complex global system modeling have connected cropland to economic variables (e.g., demand, pricing, trade), and further to a range of environmental (e.g., greenhouse gas emissions, land conversion), and social variables (e.g., population, food consumption). Examples of such models include MAgPIE (Dietrich et al., 2019) and GLOBIOM (Havlík et al., 2011). Several of the most prominent of these integrated assessment models have been used to model the Shared Socioeconomic Pathways (O'Neill et al., 2014), forecasting (among many other variables) demand for crops and the subsequent impact on cropland area under these diverse scenarios (Popp et al., 2017; Wang et al., 2020). There was important variation in the predictions of these complex models, a result of their differing underlying assumptions. This reflects the unavoidable degree of uncertainty introduced when developing such complex models to capture the full behavior of complex systems. The complexity of these models can be a weakness, limiting their broad accessibility. They are also usually limited to a calorie- or protein-centric analysis of human nutrition.

Agricultural modeling and analysis that considers future crop production often focusses on yield gaps (Lobell et al., 2009; Licker et al., 2010; Neumann et al., 2010; Mueller et al., 2012; van Ittersum et al., 2013; Fischer et al., 2014; West et al., 2014; Hatfield and Beres, 2019; Rong et al., 2021). The yield gap for a crop in a given region is essentially the difference between its measured yield and its attainable yield, though the definition and quantification of these values varies (see Fischer et al., 2014 for a discussion of the differing approaches). These analyses focus on calculating the magnitude of yield gaps, what the potential increases in productivity would be if yield gaps were closed, and the approaches needed to reduce yield gaps. Various techniques have been used to calculate yield gaps and their potential for reduction at a local or global level, many of which involve sophisticated biophysical modeling, including consideration of water use, fertilizer application and local climate. This research is extremely useful for advancing efficient and sustainable agriculture globally, and even greater benefit could be accrued by linking this research through to a more complete view of human nutritional needs.

Previously, the DELTA Model® was developed and made accessible through an online platform to allow users to explore how future global food system scenarios would meet the nutritional needs of the global population for 29 essential nutrients (Smith et al., 2021; Sustainable Nutrition Initiative®, 2021). However, the initial version of the model did not include any consideration of the resources necessary to support food production in user scenarios, such as cropland.

Here, a mathematical model was developed to calculate the cropland requirement of a future global food production scenario. This model was then incorporated into the DELTA Model®, allowing cropland requirement to be weighed against the nutritional performance of future scenarios. The framework was used to examine 2018 global cropland production, use, and nutritional performance, and its ability to model future scenarios is demonstrated.

2. Materials and methods

2.1. The DELTA Model®

The contribution of crop foods to global nutrient supply was obtained from the DELTA Model® (version 1.3; Sustainable Nutrition Initiative®, 2021). This model was fully described by Smith et al. (2021), so only an outline of the relevant aspects is included here.

The DELTA Model® uses food balance sheet (FBS) data from the United Nations Food and Agriculture Organization (FAO) for global production of food commodities in 2018 (the most recent data currently included in the model) (FAO, 2020a). The total quantity of food commodities allocated to food use in this data set is adjusted to account for inedible portions [using food item-specific coefficients from various sources (Food and Agriculture Organization, 1989; United States Department of Agriculture Economic Research Service, 1992; Rodrigues et al., 2018)] and in-home waste [using coefficients reflecting food group wastage by global region (FAO, 2011)]. The remaining quantity of food available for consumption is converted to a total quantity of 29 available nutrients using food composition data (USDA, 2020). Finally, adjustments are made to the available protein and indispensable amino acid quantities to reflect their bioavailability in individual food items (FAO, 2013).

This calculation process (Figure 1) yields a global annual quantity of nutrients at the point of human consumption that can be compared to global nutrient requirements. The DELTA Model® was designed to allow scenario analysis out to 2050. For the purposes of this article, 2018 data is analyzed, and the scope to simulate future scenarios out to 2030 is presented. Only the contribution of crop food commodities to nutrient availability and cropland dynamics are presented here; animal-sourced foods and grazing land are not included.

The DELTA Model® also uses the FBS mass allocations of each food commodity to final use. This allocation was adopted to calculate the cropland area dedicated to the various final uses. The six relevant FBS final uses are: food, animal feed, other uses (i.e., non-food, non-feed uses, such as biofuel production), processing, seed, and supply chain losses.

Here, we wished only to compare the cropland area dedicated to production of food, animal feed, and other uses. Thus, supply-chain losses and seed were assumed implicit, and not included in further calculations. All food commodities resulting from processing of a primary crop were included in the allocation of the primary crop. Finally, the proportion of the production of each food commodity allocated to food, feed, and other uses was used to identify the total area of cropland dedicated to each. A simplified example calculation is included in the Supplementary material. Thus, the total cropland area harvested for each crop was sub-divided into allocations to either human food, animal feed or other uses.

2.2. Land area calculations

The role of scenario models is to generate a range of possible futures that enable insights into the factors required for different potential outcomes. Whilst the nutrient supply that can be derived from a given set of primary food commodities is relatively determinate, the land area required for their production is subject to uncertainties and should be represented as a range of values, rather than a single point. As such, existing variability in crop yields around the world was used here to incorporate uncertainty into the model in a novel yield modeling approach.

Data for the harvested area and production mass in 2018 (the most recent available) of 137 primary agricultural crops, from 213 individual countries or territories, was obtained from the FAO online database (FAO, 2021).

The data was separated into individual crops and the list of countries producing each crop was ordered by yield (defined throughout this paper as the tons of crop produced per hectare of cropland). This allowed for calculation of overall global yield for each crop, and average yield of specific proportions of global production.

The ordered data was used to calculate the yields of the highest yielding 50 and 10% of global production, and the yields of the poorest yielding 50 and 10% of production (see Supplementary material for a graphical interpretation of this). On examination, the yield of the highest yielding 10% of production was considered not achievable in all parts of the world due to at least 30-fold differences between this value and the yield of the poorest yielding 10% of production for several crops.

For example, the highest yielding 10% of cashew nut production outperforms the global average by an order of magnitude, and outperforms the poorest yielding 10% by a factor of 30 (Table 1). Thus, achieving a global average yield of 9.38 tons per hectare does not appear feasible within the time scope of the DELTA Model®. In contrast, the variation in global soybean yields is relatively minor, meaning achieving a future global average yield equivalent to the 2018 yield of the highest 10% of production is more realistic. Wheat is also included in Table 1 as a crop with intermediate yield variation compared to cashew nuts and soybeans.

Beyond these examples, the degree of yield variation across the crops in the dataset was not consistent (Supplementary Figure S4). Following an analysis of yield variation for each individual crop in the dataset, it was assumed that the yield of the highest yielding 50% of production (hereafter referred to as HY) was a reasonable representation of an achievable global average yield by 2050 for most crops, although likely an underestimate for many staple crops. This assumption is discussed further in sections 2.2.2, 3.3.3, and 4, and could be updated as new data becomes available in the future to maintain relevance.

2.2.1. Production increases and decreases

The mathematical implementation of the model is fully described in the Supplementary material; an overview is given here. When predicting the land requirement of increases in crop production, the corresponding increase in land use was calculated assuming production at the global average yield (AY). To incorporate a range of uncertainty into these predictions, the calculation was also performed assuming increases in production at HY, or at the yield of the poorest yielding 50% of production (LY). This gives an expected cropland requirement, as well as an uncertainty range of cropland requirement needed to support the increase in production.

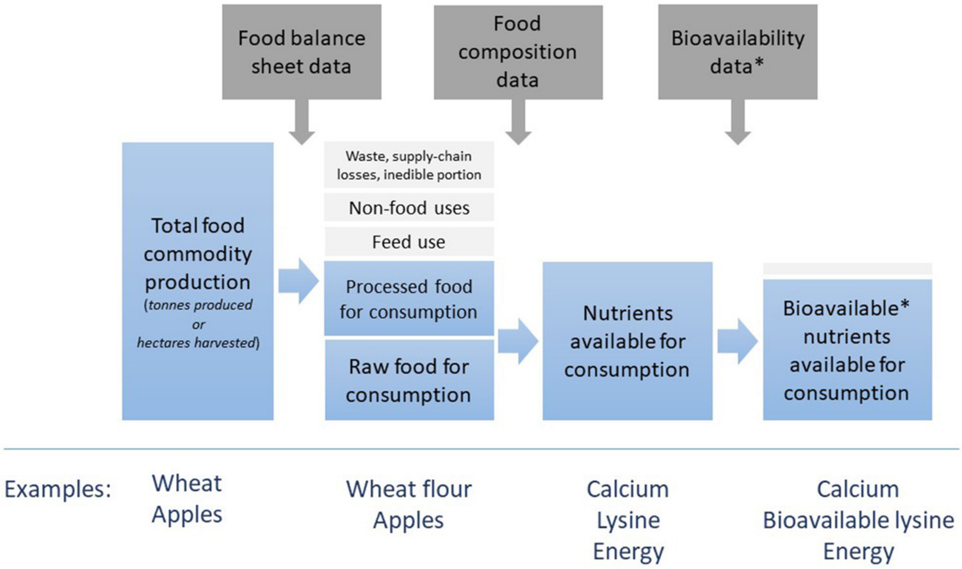


FIGURE 1
Illustration of the DELTA Model® calculation process. See section 2 for more detailed description. Some examples of food commodities, foods, and nutrients are shown for each stage of the calculation. Note that the calculation can be performed either in units of tons, or hectares of primary crop harvested. *Bioavailability coefficients are applied to protein and the indispensable amino acids only. Adapted from Smith et al. (2022b).

TABLE 1 Yield characteristics (tons per hectare) of selected global crop production in 2018, calculated using data from FAO (2021).

	Global average yield	Highest yielding 10% of production	Highest yielding 50% of production	Poorest yielding 50% of production	Poorest yielding 10% of production
Cashew nuts	0.99	9.38	8.98	0.53	0.31
Soybeans	2.79	3.47	3.45	2.35	1.39
Wheat	3.43	7.02	4.88	2.64	1.79

A similar approach was taken for decreases in production. It was calculated that any decreases may occur on land producing at AY, at HY, or at LY.

In a scenario of decreased crop production, the lower estimate for land area requirement is based on decreases at LY for a production decrease of up to 50%, after which HY is used for any further reduction. Conversely, the upper estimate for land area requirement in a scenario of decreased production is based on decreases at HY for a production decrease of up to 50%, after which LY is used for any further reduction. See the Supplementary material for graphical examples of these reductions.

To be compatible with the DELTA Model® visual outputs, it was necessary to aggregate individual crop data into nine crop groups (cereals, fruits, nuts, pulses, starchy roots, sugar, other plants, vegetables, and oilcrops). This was performed additively: upper bound estimates for the crop group are the sum of the upper bound estimates for all constituent crops, and similarly for lower bounds and the expected value.

2.2.2. Yield improvements

In addition to increases and decreases in production, it is also possible for the yield of existing land used to produce crops to increase or decrease its yield. Two possibilities for modeling this were considered.

The first approach is to apply a simple yield change coefficient to all existing yield values. For example, under the assumption that global yields for a crop will increase by 20%, the land area required to produce the same amount of the crop will decrease reciprocally to 83% of the original value. This coefficient can also be applied to upper and lower bounds when making predictions about changes to production quantity.

Whilst simple and transparent, this approach does not account for the extent to which yield of a crop is already approaching sustainable production limits, thus may result in unachievably high yield estimates if unconstrained yield change coefficients are used. Constraining these coefficients would require data for global yield gaps for all modeled crops, which are not currently available.

A second approach is to assume that HY constitutes a realistic estimate of the average yield that may be possible globally, as described above. The limitations of this assumption are presented in the section 4. A productivity improvement factor between 0 and 100% can then be applied, representing the proportion of production at LY that is improved to producing at HY. This approach was selected for use in this model. See the Supplementary material for a graphical example of this.

Let the "optimistic case" be defined as assuming 100% of LY land is improved to producing at HY. In this case, the optimistic global average yield is simply equal to the original HY. To calculate the upper and lower bounds in the optimistic case, the HY and LY for the optimistic case were calculated, i.e., the yield of the highest yielding 25% of original production, and the yield of the second-highest yielding 25% of original production. These values are used as the HY and LY for the optimistic case, and the upper and lower bounds on estimates can be calculated using these values. For productivity improvements of <100%, a scaled linear combination of the original yield values and the optimistic case yield values are used.

3. Results

3.1. Global land use for crops

Figure 2 gives an overview of the 2018 crop production and cropland area reported by the FAO (2021), divided into nine major crop groups. These data capture the total mass of food commodities leaving the farm gate, so exclude harvesting losses (FAO, 2020a). Both production and area harvested were dominated by cereals. The next highest production crop groups were sugar and vegetables, whereas oilcrops had the next greatest area harvested after cereals.

The uses of the produced crops varied between the food groups. The FAO FBS allocate crop commodity mass to end uses. Translating these allocations to the cropland area producing these commodities it was found that, of the overall cropland area in 2018, 66% was used to produce human food, 18% to produce animal feed, 14% to produce crops for other uses (e.g., biofuel production), and 1% was used to produce non-food crops (e.g., rubber).

However, note that this allocation method hides some information: for example, of the 795 million hectares of cropland allocated to human food production, around 12% was used to produce soyabeans. The production of soyabeans results in both soyabean products for human consumption and soyabean cake for animal feed, yet soyabean cake is not captured by the FBS as it is not considered a food commodity. Thus, the allocations above must not be interpreted as representative of the relative mass allocated to different uses, but rather the primary purpose of crop production, and exclusive of by-product use. The allocation breakdown for each crop group is shown in Table 2.

3.2. Current nutritional contribution of plant foods

Using the DELTA Model® (version 1.3; Sustainable Nutrition Initiative®, 2021), the contribution of crops to global nutrient availability from food in 2018 was established (Figure 3). These results are presented in tabular form in the Supplementary material.

Plant foods were responsible for at least 50% of global availability for most nutrients included in the model. The exceptions were calcium, vitamin B12 and the indispensable amino acids lysine, methionine, and threonine. Within the plant food groups, cereals were the major contributor to the availability of most nutrients, partly due to their high production totals: cereals constituted approximately one third of global crop mass leaving the world's farms. The exceptions to this were: fat and vitamin E, which were predominantly sourced from oilcrops; calcium, potassium, and vitamins A, B9, and C, to which vegetables were the greatest contributing group. The remaining crop groups (constituting 44% of global crop mass), had varying and comparatively minor contributions to global nutrient availability. Sugar crops, despite constituting 25% of 2018 crop mass, had a minimal impact on nutrient availability. This was due to a combination of the limited nutritional value of sugar crops, the high proportion of mass lost during processing, and the high proportion of mass directed to non-food uses, such as biofuel production.

3.3. Forecasting future changes in cropland requirement

To see the effect on predicted land requirement, global production of each major crop group was increased by 50% in the model. Following the calculation methodology, the predicted increase in land area required also increased by 50% for all crop groups, but the upper and lower estimates varied between groups. For most crop groups, the increase estimate ranged from ∼ 25 to 75% above the 2018 total cropland area required for production. However, for the nuts group, the increase estimate ranged from 14 to 86%, reflecting the high global variability in nut crop yields. Contrastingly, the increase estimate for sugar crops ranged from 42 to 58%, due to the low global variability in yields of these crops.

3.3.1. Analysis of individual crops

The individual crop with the greatest potential for productivity gain when comparing HY with LY was cashew

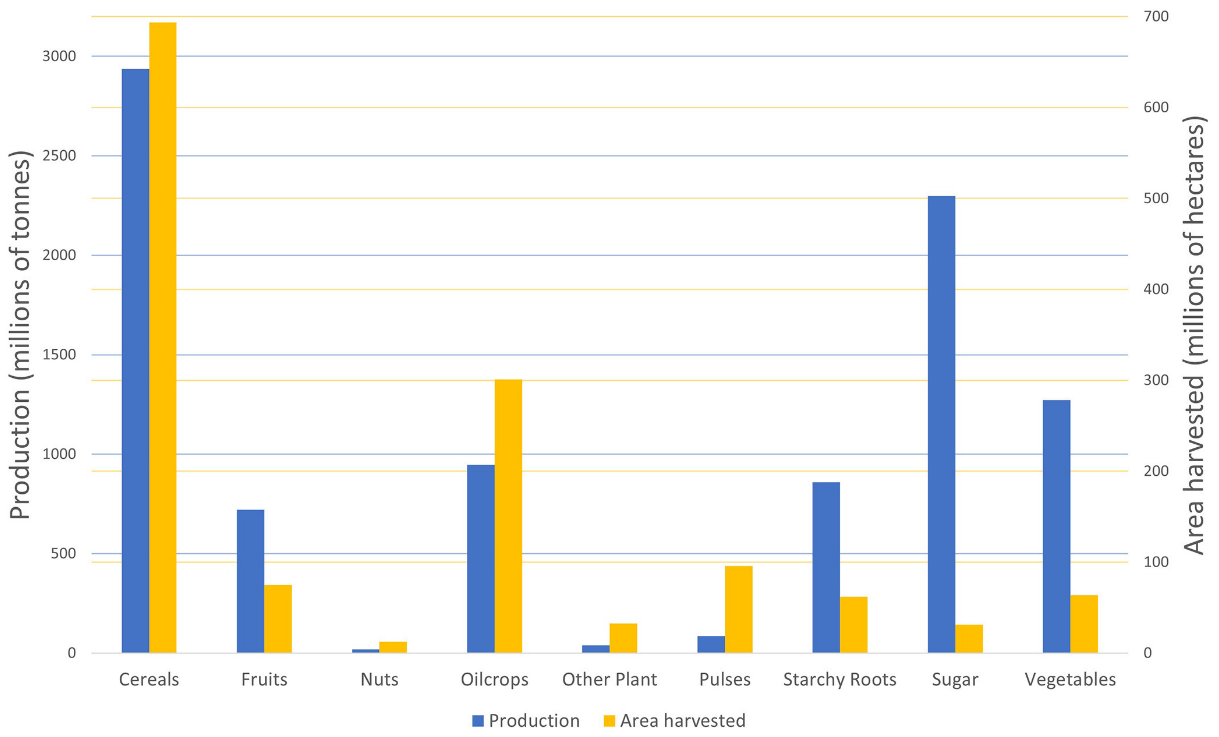


FIGURE 2
2018 crop production and cropland area harvested by major crop group (FAO, 2021).

TABLE 2 Allocation of 2018 cropland area harvested to final use.

	Total area harvested (million hectares)	Allocation		
		Human food (%)	Animal feed (%)	Other uses (%)
Cereals	694	55	34	11
Fruits	75	99	1	<0.5
Nuts	13	99	0	<0.5
Oilcrops	301	57*	5	38
Other plant	33	96	<0.5	4
Pulses	96	77	22	1
Starchy roots	62	70	22	8
Sugar	31	66	7	27
Vegetables	64	95	5	<0.5

Percentages may not sum to 100% due to rounding.
*Although 57% of oilcrops land was allocated to food, 37% of oilcrops land was used for soyabean production.
See Supplementary material for detailed calculation methodology.

nuts: the LY/HY ratio for this crop was 0.06. This was followed by papayas (0.13), pistachios (0.18), and mushrooms and truffles (0.19). Papayas contributed around 2% of 2018 fruit production, while mushrooms and truffles were < 1% of vegetable production. In contrast, cashew nuts and pistachios together constituted around 40% of nut production in 2018, but the contribution of nuts to global nutrient availability was minor (Figure 2). Thus, these crops with low LY/HY ratios made relatively minor contributions to human nutrition. All other crops had an LY/HY ratio of at least 0.2.

Contrastingly, the individual crops with the least potential for productivity gain using the LY/HY ratio were cassava leaves

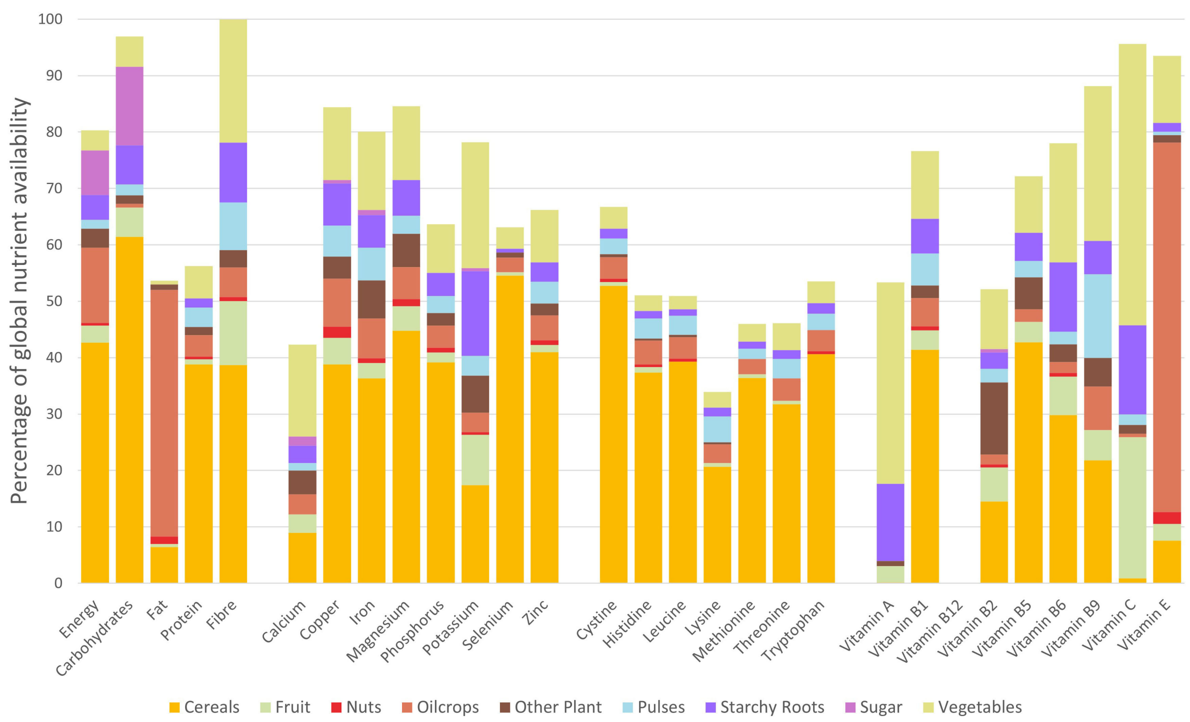


FIGURE 3
Contribution of plant foods to global nutrient availability. These values were calculated using the DELTA Model® (version 1.3; Sustainable Nutrition Initiative®, 2021), so have been adjusted for waste, inedible portions, and bioavailability as described in section 2.

(0.99; however, this only includes data from two countries: Congo and Colombia), cashewapple (0.97; includes data from four countries), and asparagus (0.91). Again, these crops at the other extreme of LY/HY ratio were minor contributors to global nutrient availability. The full list is included in the Supplementary material.

Using the productivity gains approach, the individual crops that showed the greatest potential for reduction of land use by improving poor yielding production could be investigated. Assuming all production at LY were improved to HY, the individual crops that would reduce their land footprints by the greatest amount were found. The crops at the top of this list were the major cereal crops: maize (reduction of 81 million hectares, or 42% of current land growing maize), wheat (63 million hectares, 30%), and rice (36 million hectares, 28%). These crops differ from those with the greatest potential for productivity gains as they occupy greater areas of land, hence have a greater potential for global cropland use reduction.

The increased production on the same land footprint that could be achieved if all production were improved to HY showed similar rankings. In this case, an extra 829 million tons of maize (72% increase), 312 million tons of wheat (42% increase), and 259 million tons of rice (38% increase) could be produced from the same land area as was used for these crops in 2018.

3.3.2. Analysis of crop groups

Table 3 shows the crop data aggregated to crop groups. The crop group with the greatest potential for productivity gains was nuts: the LY/HY ratio for this group was 0.16. This was followed by oilcrops (0.33) and other plant (0.33). Contrastingly, the crop groups with the least potential for productivity gain using this ratio were sugar (0.79) and vegetables (0.53).

Assuming all production at LY were improved to HY, the crop groups that would reduce their land footprints by the greatest amount were: cereals, with a possible reduction of 278 million hectares (40% of land currently producing cereals); followed by oilcrops (152 million hectares; 50%); and pulses (38 million hectares, 39%). At the other extreme, only 3.6 million hectares of sugar crop land would be saved (12%) and 9.1 million hectares of land producing nuts (although this constituted 73% of the land producing nuts in 2018).

The increase in production without increasing land footprint that could be achieved under global HY conditions was also dominated by the crop groups occupying the greatest land area. In this case, an extra 1.9 billion tons of cereals (67% increase), 957 million tons of oilcrops (102% increase), and 618 million tons of starchy roots (74% increase) could be produced from the same cropland area as was used for these crop groups in 2018.

TABLE 3 Aggregated results by crop group for production, area harvested, yield and outcomes if HY were achieved for all crops globally.

Crop group	Production (millions of tons)	Area harvested (millions of hectares)	Global average yield (tons per hectare)	HY (tons per hectare)	LY (tons per hectare)	LY/HY	Land saved if all production were at HY			Additional production on the 2018 land footprint if all production were at HY	
							Millions of hectares	% of 2018 land used for this crop group	% of 2018 global cropland	Millions of tons	% increase in production compared to 2018
Cereals	2,857	694	4.1	6.9	2.9	0.43	278	40%	20%	1,913	67%
Fruits	850	75	11.4	17.6	8.4	0.48	26	35%	2%	467	55%
Nuts	18	13	1.4	5.3	0.8	0.16	9	73%	<1%	48	264%
Oilcrops	940	301	3.1	6.3	2.1	0.33	152	50%	11%	957	102%
Other plant	35	33	1.1	2.1	0.7	0.33	16	50%	1%	35	101%
Pulses	92	96	1	1.6	0.7	0.44	38	39%	3%	60	65%
Starchy roots	832	62	13.4	23.4	9.4	0.40	26	43%	2%	618	74%
Sugar	2,183	31	70	79.1	62.7	0.79	4	12%	<1%	285	13%
Vegetables	1,117	64	17.5	25.3	13.4	0.53	20	31%	1%	498	45%

10.3389/fsufs.2022.1063419

3.3.3. Comparison to yield gap modeling

Several yield gap publications have calculated the potential increase in mass of specific crops if production were to achieve attainable or potential yields globally. Table 4 compares these estimates with the results found here.

The existing estimates use varying methodologies and data sources, and most rely on data recorded between 2000 and 2010, whereas this work uses 2018 data. The Global Yield Gap and Water Productivity Atlas is continuously updated and includes more recent data than the other publications used in this comparison.

The potential production increases calculated vary by 2–87% between the different yield gap analyses but are all greater than the potential increases calculated here, with the exception of the maize estimate from Mueller et al. (2012).

To check the sensitivity of these results to the definition of HY, the potential production increases were also calculated assuming HY represented the average yield of the best performing 10% of crop production, rather than the best 50%. In this instance, the potential production increases for rice (45%) and soy (24%) changed little. However, the increases for maize (101%) and wheat (105%) were significant, but still within the range observed in the literature.

3.3.4. Scenario example

To illustrate the use of the cropland area forecasting technique described here, it was implemented in the DELTA Model® framework to compare 2018 cropland requirement with 2030 cropland requirement if all crop production were to increase at the same rate as the forecast global population [i.e., increasing 12% from 7.6 billion people in 2018 to 8.5 billion people in 2030 (United Nations, Department of Economic and Social Affairs, Population Division, 2019)]. The results are shown in Figure 4.

The model predicted a matching 12% increase in cropland requirement over 2018 to support the increased production, with lower and upper bounds of 7 and 17% increases, respectively. However, improving 30% of global LY crop production to HY for all crops in this scenario was predicted to reduce cropland requirement to within 1% of the 2018 requirement. The upper and lower bounds for this estimate were a 4% increase and a 3% decrease compared to 2018, respectively.

The nutritional outcomes of these 2030 scenarios were similar to the 2018 scenario: under the assumption that non-food use of crops remained constant, per capita energy, protein, and fat availability would change by <3%, as the population increase would be matched by increased crop production. The availability of most other nutrients changed by <6% from 2018 levels. The exception was vitamin B12, per capita availability of which fell by ∼ 10% due to being sourced almost exclusively from animal-sourced foods, production of which was held constant in this simulation.

4. Discussion

The DELTA Model® has been used to analyse the nutrient adequacy of current and future global food system scenarios (Smith et al., 2021; Sustainable Nutrition Initiative®, 2021). Broadening the scope of the model to include the cropland requirement of global food system scenarios, as detailed here, begins the task of including the resource footprints and environmental impacts of food production in the model. It also allows policy and research users to see the interrelationships and trade-offs between human nutrition and land use in future food production scenarios.

4.1. Analysis of findings

That crop production (and cereals in particular) should have a major role in the delivery of nutrition to the global population, as calculated here, is unsurprising. Also clear is the minor role of sugar crops in nutrition, despite their high contribution to global crop mass. However, sugar crops showed the least variation in yields of all crop groups. This is likely due to the dominance of sugar crop production by a few countries; for example, around 60% of global sugar cane is produced by Brazil and India. Sugar cane also uses C4 photosynthesis, increasing their photosynthetic, water, and nitrogen-use efficiency compared to crops using C3 photosynthesis, likely contributing to these minor yield variations compared to most food crops (Sage et al., 2013). Sugar crops occupy a relatively small land area at 31 million hectares (∼2% of global cropland). Thus, although sugar crops are poor contributors to human nutrition, little cropland could be gained for production of other crops or alternative uses by reducing sugar production or by raising the productivity of poorer yielding sugar production to best practice.

Contrastingly, the production of both individual nut crops and the nut crop group showed wide variation in global yields. This is in part due to the dominance of production by individual nations. For example, the USA was responsible for 59% of global almond production on just 21% of the global area harvested for almonds, while Viet Nam produced 45% of cashew nuts on <5% of the global area harvested. The remainder of production was sourced from a high number of low producing countries, meaning that HY largely reflects the performance of a single country. In these instances, it must be asked whether the performance of these dominant countries can be replicated by the rest of the nut-producing world, or whether the production in these high-yielding countries can be further increased.

It has been suggested that nut crops should be more widely produced and consumed due to their nutrient density and reduced carbon footprint, compared to many other protein sources (Clune et al., 2017; Afshin et al., 2019; Willett et al., 2019). However, others have raised concerns over the protein quality (Rutherfurd et al., 2014; Chalupa-Krebzdak et al., 2018;

TABLE 4 Comparison of potential increase in production of specific crops calculated by differing sources using various methodologies.

Crop	Production increase if all 2018 cropland production were at HY (%)	Production increase if yield gaps were closed (%)			
		Fischer et al., 2014	Mueller et al., 2012	Neumann et al., 2010	GYGA*
Maize	72	98	64	100	106
Rice	39	72	47	56	102
Soybeans	23	30	ND	ND	106
Wheat	42	50	71	56	137

ND, no data; GYGA, global yield gap atlas.
*See Global Yield Gap and Water Productivity Atlas. Available online at: www.yieldgap.org, van Ittersum et al. (2013), and Schils et al. (2018).

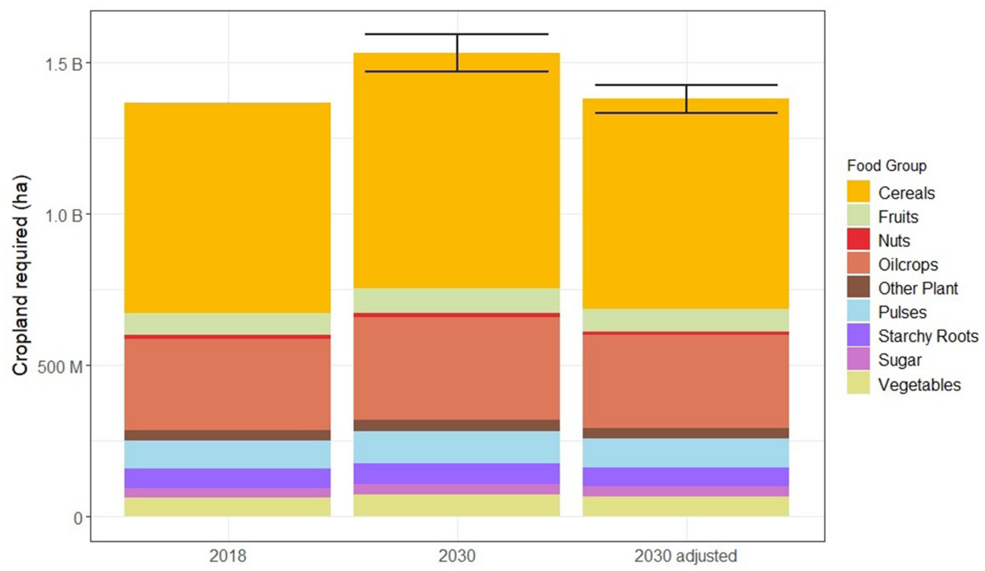


FIGURE 4
Comparing cropland requirement in 2018 with two simulated scenarios. The 2030 scenario shows predicted cropland requirement if all crop production were to increase by 12%, to match the population increase from 2018 to 2030. The 2030 adjusted scenario is identical, but 30% of LY production has been improved to HY. Error bars indicate the upper and lower bounds of the prediction.

Wolfe et al., 2018) and high contributions to water use and water scarcity of nut production (Ridoutt et al., 2018; Sokolow et al., 2019). The results presented here pertain only to the yields of nut production, which show the greatest potential for improvement toward best practice of all crop groups.

However, the greatest potential for increasing food production on existing land was found for the staple crops. Although these crops showed smaller differences between HY and LY than nuts, the far larger areas of cropland dedicated to their production means that even minor gains in productivity would translate to large increases in production. However, whether increases in production of these crops should be targeted must be questioned. From a nutritional perspective, staple crops are high contributors to energy and macronutrient availability, as well as some specific minerals (e.g., iron, zinc). However, the DELTA Model® shows that it is micronutrients, rather than macronutrients, that are limiting global nutrient availability, and that the staple crops are not the densest sources of these nutrients (Smith et al., 2021; Sustainable Nutrition Initiative®, 2021). Other food groups, such as vegetables, nuts, and certain animal-sourced foods may be better options from the perspective of delivering global nutrient sufficiency.

A separate issue is the use of crops once harvested. Although the majority of all crop production modeled was allocated to human food use, more than a quarter of sugar crop mass and more than a third of oilcrop mass leaves the food system entirely for other uses, such as biofuel production (FAO, 2021).

The efficiency of this cropland use for delivering nutrition is therefore poor, and this fact should be weighed against the benefits of these other uses.

The two future scenarios presented in Figure 3, one in which crop production increases with the population, and a second in which this occurs with a 30% productivity gain across all crop groups, are merely illustrations of the potential use of the model. It is almost certain that increases in production and changes to productivity will not be uniform across all crop groups in the future. However, the model can indicate the likely cropland requirement of future production systems, as well as showing the degree of uncertainty in these predictions.

4.2. Limitations

Due to the number of countries included in the analysis, we have not reported here results at a geographic level, such as where individual countries rank for production or yield of crops or crop groups. This would be a large exercise, beyond the scope of this work. This data is accessible online alongside the DELTA Model® (www.sustainablenutritioninitiative.com).

Uncertainty in estimating future cropland requirement stems from multiple factors. Crop yields are dependent on soil quality, crop genetics, weather, management practices, the rate of crop development, and several other factors. Moreover, these factors vary in importance between different crops. As such, forecasting the land required to produce a certain amount of a crop or crop group globally requires a high degree of generalization. The limitations of such top-down approaches are well-discussed in yield gap modeling, with the aggregation of localized, crop-specific, biophysical, bottom-up data to form a global picture presented as a more accurate approach (van Ittersum et al., 2013; Fischer et al., 2014; Rattalino Edreira et al., 2021). However, given the current absence of such data for many crops, top-down empirical approaches must suffice.

The FAO national crop production and area harvested data were chosen here for their broad coverage of global production and regular data updates, allowing for modeling estimates to be updated over time. However, the FAO data has several limitations. Data at a national level does not allow the variation at a sub-national level to be ascertained, which is high in some countries with regional variation in production practices and climate (Arata et al., 2020; Liu et al., 2021). There are also countries that are not included in the FAO dataset, and the quality of data included will vary between reporting authorities.

It should also be noted that solely 2018 crop data was used here. Others have analyzed temporal changes in crop yields using FAO and other datasets (see Arata et al., 2020 and references therein). These analyses are important for forecasting future changes to crop yields, which can be incorporated into cropland requirement forecasting.

To account for the variability in crop yields when forecasting increases and decreases in production in the future, the AY, HY, and LY for each crop was calculated. The choice of the average yield of the upper and lower yielding halves of production to represent bounds on predictions is worthy of discussion. Alternative choices, such as the highest and lowest yielding 10% of production as HY and LY [as has been used at regional and global scales for selected crops elsewhere (Licker et al., 2010; Laborte et al., 2012; Liu et al., 2021)], or specific bounds based on the yield characteristics of individual crops were considered, and compared to the results of yield gap analysis in section 3.3.3.

The choice of a 50% threshold for HY and LY was made due to the global resolution of the model and the diversity of crops included. The 10% thresholds used elsewhere were justified by a greater understanding of attainable yields, through the use of more localized data, often including climatic, management, and soil quality data. A similar approach here would have necessitated either the user or the model making decisions on the location of changes to production for the modeled crops. This added degree of complexity risked impairing the transparency of the model or the simplicity of its use, which were given greater priority due to the intended use of the model by a broad range of stakeholders. Improving low yields to HY was thus assumed attainable for most crops in most producing regions, regardless of fixed climatic and geographical constraints.

It is likely that for some crops, improving a large proportion of LY production to HY will not be possible. The highest yielding countries for a crop often have climatic, geographical, and technological advantages over the poorer yielding countries. Some of these barriers will be impossible to overcome, meaning that the modeled improvements will not be achievable. Even where such improvements are achievable, they may come with changes to management practices, such as higher use of fertilizers, pesticides, or irrigation. The trade-offs necessary to implement these practices, such as financial and environmental costs, should be considered in addition to yield outcomes (Fischer et al., 2014). As holistic a view of outcomes as possible is desirable when considering future changes to crop production. The method presented here does not capture all of these outcomes but was chosen as a transparent and intuitive generalizable approach.

As well as forecasting the cropland requirement of changes in total crop production, it was also necessary to consider the impacts of increasing crop yields on existing land. The approaches considered: linear increases to global average yields, or productivity gains *via* proportionally increasing land at LY to HY, each have advantages and disadvantages. While the former allows for yields to be achieved that are above current best practice due to future improvements in crop technology and management and is most analogous to existing yield gap approaches, the degree of possible improvement will vary between crops. The comparison of our results with those obtained in yield gap modeling in Table 3 demonstrates that, for the four major crops analyzed, our estimates of potential increases in production should be considered conservative. This is likely due to the fact that we do not allow for current high yielding production to be further improved, whereas previous yield gap analyses consider the possible improvement of all cropland more locally. The conservative nature of our estimates for the staple crops should not necessarily be extrapolated to other crops: there is a paucity of yield gap data for most food crops, preventing any conclusions on this.

Finally, the modeling approach presented here has not considered the varied characteristics of different cropland. The use of total cropland area as a metric has been criticized as not capturing the locally specific impacts of land use. Ridoutt and Navarro Garcia (2020) proposed metrics such as cropland scarcity, cropland malnutrition footprint, and cropland biodiversity footprint as alternatives that better capture the complexities of land suitability for specific crops. While these are powerful tools for local decision making, they were not included here due to the challenges of sufficient global data and intuitive ease of interpretation. Instead, the approach produced in this paper allows for rapid calculation and easy understanding of the implications of future changes to global food production on cropland use and its connection to human nutrition.

4.3. Recommendations for future study

Future work could use alternative methods for the consideration of specific crops, and indeed this approach has been taken by others. For example, Liu et al. (2021) considered China's total attainable maize and soy production if all production in each Chinese county was able to achieve the yields of the best performing 10% of production in that county. The use of the best performing 10% as the attainable level was considered appropriate given the individual crop and county resolution of the modeling approach. In contrast, given the global perspective of the modeling presented here, the best performing 50% was selected as a more appropriate estimate of an attainable global average.

As mentioned in the introduction, yield gap analysis is a common approach in researching future cropland requirement (Cassman et al., 2003; Lobell et al., 2009; Neumann et al., 2010; Mueller et al., 2012; Fischer et al., 2014; West et al., 2014; Hatfield and Beres, 2019; Rong et al., 2021). Frequently, average crop yields are found to plateau at around 80% of the potential yield, often due to the increasing financial costs of incremental production gains (Lobell et al., 2009; van Ittersum et al., 2013; Fischer et al., 2014). Using yield gaps in predictive modeling is limited by the availability of global data, which is only available for the most widely grown crops.

Previous research has shown that even staple crops such as wheat, maize and rice are not grown at full potential yields in the majority of producing countries (Lobell et al., 2009; Neumann et al., 2010; Hatfield and Beres, 2019; Rong et al., 2021). Thus, modeling linear yield increases may be appropriate for certain crops.

The method of productivity gains applied here does not allow for possible large improvements in attainable yields due to technological advancement. However, bringing global yields closer to best practice is more realistic when simultaneously considering all crop species. Future work could combine the approaches of linear increases in yield and the productivity gains presented here with consideration of yield gaps for individual crops.

Current and future reductions in the yields of certain crops in most parts of the world due to climate change have been identified, with particular focus on wheat, rice, maize, and soy (Lobell et al., 2011; Challinor et al., 2014; Zhao et al., 2017; Ray et al., 2019). It has been estimated that year-by-year climate variability already accounts for around a third of observed yield variability in major crop varieties (Ray et al., 2015); this variability may increase in many regions as climatic conditions diverge from previous averages. To model such future scenarios, linear decreases to crop yields or shifts of HY production to LY could be simulated. These approaches were beyond the scope of this work but should feature in future modeling.

Climate change is also likely to have an impact on the nutritional value of crops. Crops grown experimentally at elevated CO_2 concentrations generally showed higher yields given sufficient nutrient and water availability, but also both positive and negative impacts on nutrient content (Myers et al., 2014; Dong et al., 2018). A full understanding of these impacts on nutrients in a wider range of crops would allow for these changes to be included in the nutritional calculations for future scenarios.

The FAO reported that cropland covered around 1.4 billion hectares in 2018, a rise of 20% since 2000 (FAO, 2020b). The potential for increasing cropland area without conversion of non-agricultural land lies largely in land currently used for animal grazing. It has been estimated that, of the close to two billion hectares of 2010 global grazing land, 685 million hectares was suitable for crops (Mottet et al., 2017). This sets an upper limit on cropland area (without conversion of non-agricultural land) of around 2.1 billion hectares, comparable to estimates elsewhere (Rockström et al., 2009; Henry et al., 2018). However, the conversion of grassland to crops would result in a reduction of available grazing land, with an impact on animal production. As implied by Figure 3, animal-sourced foods are major contributors to nutrient availability, particularly vitamin B12 from meat and calcium from dairy (Smith et al., 2022a,b). Any reductions in animal production due to cropland expansion may have consequences for nutrient availability from these sources. Moreover, further expansions in cropland are concerns for both biodiversity (Delzeit et al., 2017; Usubiaga-Liaño et al., 2019) and carbon balance (Engström et al., 2017). These factors must feature in any model attempting to capture the full scope of impacts of cropland expansion.

5. Conclusion

Forecasting the future dynamics of the global food system is clearly challenging given the high number and magnitude of the uncertainties involved. However, such forecasting will be key to inform shifts toward more sustainable crop production and achieving global nutrient adequacy. The modeling presented here allows for the simultaneous calculation of cropland footprint and nutrient availability in future scenario modeling. The insights generated by the DELTA Model® demonstrate the nutritional importance of current crop production and the potential cropland and nutritional outcomes of productivity gains in individual crops and crop groups. Unifying the nutritional value of production with the cropland area necessary to achieve it allows the sustainability of future food system scenarios to be assessed against both these criteria. The model should be used in future policy discussion and research to quantify the connections between human nutrition and land use, to avoid situations where one or the other is excluded from decision making.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

NS, AF, JH, and WM conceived the idea for the research. NS and AF undertook the modeling and data analysis. All authors contributed to the writing and reviewing of the manuscript.

Acknowledgments

The authors thank the many international scientists who provided beneficial feedback on the cropland modeling in the DELTA Model®. We also thank Charlotte van der Lee and Sarah Golding for their inputs into the development of this model, and the Riddet Institute for their support of the research undertaken by the Sustainable Nutrition Initiative®. The authors thank the Global Yield Gap Atlas team for sharing relevant yield gap data.

Conflict of interest

AF and JH were employed by Fonterra Research and Development Centre. PM was employed by Manaaki Whenua Landcare Research.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1063419/full#supplementary-material

SUPPLEMENTARY DATA SHEET 1
Calculation methodology, calculation example, and supplementary figures.

SUPPLEMENTARY DATA SHEET 2
Nutrient contribution of crop production to global nutrient supply.

SUPPLEMENTARY DATA SHEET 3
Crop-level yield metrics.

References

Afshin, A., Sur, P. J., Fay, K. A., Cornaby, L., Ferrara, G., Salama, J. S., et al. (2019). Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the global burden of disease study 2017. *Lancet* 393, 1958–1972. doi: 10.1016/S0140-6736(19)30041-8

Arata, L., Fabrizi, E., and Sckokai, P. (2020). A worldwide analysis of trend in crop yields and yield variability: evidence from FAO data. *Econ. Model.* 90, 190–208. doi: 10.1016/j.econmod.2020.05.006

Cassman, K. G., Dobermann, A., Walters, D. T., and Yang, H. (2003). Meeting cereal demand while protecting natural resources and improving environmental quality. *Annu. Rev. Environ. Resour.* 28, 315–358. doi: 10.1146/annurev.energy.28.040202.122858

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., and Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nat. Clim. Change* 4, 287–291. doi: 10.1038/nclimate2153

Chalupa-Krebzdak, S., Long, C. J., and Bohrer, B. M. (2018). Nutrient density and nutritional value of milk and plant-based milk alternatives. *Int. Dairy J.* 87, 84–92. doi: 10.1016/j.idairyj.2018.07.018

Clune, S., Crossin, E., and Verghese, K. (2017). Systematic review of greenhouse gas emissions for different fresh food categories. *J. Clean. Prod.* 140, 766–783. doi: 10.1016/j.jclepro.2016.04.082

Delzeit, R., Zabel, F., Meyer, C., and Václavík, T. (2017). Addressing future trade-offs between biodiversity and cropland expansion to improve food security. *Reg. Environ. Change* 17, 1429–1441. doi: 10.1007/s10113-016-0927-1

Dietrich, J. P., Bodirsky, B. L., Humpenöder, F., Weindl, I., Stevanović, M., Karstens, K., et al. (2019). MAgPIE 4 – a modular open-source framework for modeling global land systems. *Geosci. Model Dev.* 12, 1299–1317. doi: 10.5194/gmd-12-1299-2019

Dong, J., Gruda, N., Lam, S. K., Li, X., and Duan, Z. (2018). Effects of elevated CO2 on nutritional quality of vegetables: a review. *Front. Plant Sci.* 9, 924. doi: 10.3389/fpls.2018.00924

Engström, K., Lindeskog, M., Olin, S., Hassler, J., and Smith, B. (2017). Impacts of climate mitigation strategies in the energy sector on global land use and carbon balance. *Earth Syst. Dynam.* 8, 773–799. doi: 10.5194/esd-8-773-2017

Engström, K., Rounsevell, M. D. A., Murray-Rust, D., Hardacre, C., Alexander, P., Cui, X., et al. (2016). Applying Occam's razor to global agricultural land use change. *Environ. Model. Softw.* 75, 212–229. doi: 10.1016/j.envsoft.2015.10.015

FAO (2011). *Global Food Losses and Food Waste - Extent, Causes and Prevention*. Rome: United Nations Food and Agriculture Organisation.

FAO (2013). "Dietary protein quality evaluation in human nutrition," in *FAO Food and Nutrition Paper* (Auckland, NZ: United Nations Food and Agriculture Organisation). Available online at: https://www.fao.org/documents/card/en/c/ab5c9fca-dd15-58e0-93a8-d71e028c8282/

FAO (2020a). *FAO Food Balance Sheets*. United Nations Food and Agriculture Organization. Available online at: http://www.fao.org/faostat/en/#data/FBSH (accessed October 29, 2021).

FAO (2020b). *World Food and Agriculture - Statistical Yearbook 2020*. Rome: FAO.

FAO (2021). *FAOSTAT*. Available online at: : http://www.fao.org/faostat/en/#home (accessed April 20, 2020).

Fischer, R., Byerlee, D., and Edmeades, G. (2014). *Crop Yields and Global Food Security: Will Yield Increase Continue to Feed the World?* Canberra, ACT: ACIAR.

Food and Agriculture Organization (1989). *Yield and Nutritional Value of the Commercially More Important Fish Species*. Rome: FAO.

Hatfield, J. L., and Beres, B. L. (2019). Yield gaps in wheat: path to enhancing productivity. *Front. Plant Sci.* 10:1603. doi: 10.3389/fpls.2019.01603

Havlík, P., Schneider, U. A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., et al. (2011). Global land-use implications of first and second generation biofuel targets. *Energy Policy* 39, 5690–5702. doi: 10.1016/j.enpol.2010.03.030

Henry, R. C., Engström, K., Olin, S., Alexander, P., Arneth, A., and Rounsevell, M. D. A. (2018). Food supply and bioenergy production within the global cropland planetary boundary. *PLoS ONE* 13, e0194695. doi: 10.1371/journal.pone.0194695

Laborte, A. G., De Bie, K., Smaling, E. M. A., Moya, P. F., Boling, A. A., and Van Ittersum, M. K. (2012). Rice yields and yield gaps in Southeast Asia: past trends and future outlook. *Eur. J. Agron.* 36, 9–20. doi: 10.1016/j.eja.2011.08.005

Licker, R., Johnston, M., Foley, J. A., Barford, C., Kucharik, C. J., Monfreda, C., et al. (2010). Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? *Global Ecol. Biogeogr.* 19, 769–782. doi: 10.1111/j.1466-8238.2010.00563.x

Liu, Z., Ying, H., Chen, M., Bai, J., Xue, Y., Yin, Y., et al. (2021). Optimization of China's maize and soy production can ensure feed sufficiency at lower nitrogen and carbon footprints. *Nat. Food* 2, 426–433. doi: 10.1038/s43016-021-00300-1

Lobell, D. B., Cassman, K. G., and Field, C. B. (2009). Crop yield gaps: their importance, magnitudes, and causes. *Annu. Rev. Environ. Resour.* 34, 179–204. doi: 10.1146/annurev.environ.041008.093740

Lobell, D. B., Schlenker, W., and Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science* 333, 616–620. doi: 10.1126/science.1204531

Molotoks, A., Stehfest, E., Doelman, J., Albanito, F., Fitton, N., Dawson, T. P., et al. (2018). Global projections of future cropland expansion to 2050 and direct impacts on biodiversity and carbon storage. *Global Change Biol.* 24, 5895–5908. doi: 10.1111/gcb.14459

Mora, O., Le Mouël, C., De Lattre-Gasquet, M., Donnars, C., Dumas, P., Réchauchère, O., et al. (2020). Exploring the future of land use and food security: a new set of global scenarios. *PLoS ONE* 15, e0235597. doi: 10.1371/journal.pone.0235597

Mottet, A., De Haan, C., Falcucci, A., Tempio, G., Opio, C., and Gerber, P. (2017). Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Glob. Food Sec.* 14, 1–8. doi: 10.1016/j.gfs.2017.01.001

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., and Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature* 490, 254–257. doi: 10.1038/nature11420

Myers, S. S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A. D. B., Bloom, A. J., et al. (2014). Increasing CO2 threatens human nutrition. *Nature* 510, 139–142. doi: 10.1038/nature13179

Neumann, K., Verburg, P. H., Stehfest, E., and Müller, C. (2010). The yield gap of global grain production: a spatial analysis. *Agric. Syst.* 103, 316–326. doi: 10.1016/j.agsy.2010.02.004

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., et al. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* 122, 387–400. doi: 10.1007/s10584-013-0905-2

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., et al. (2017). Land-use futures in the shared socio-economic pathways. *Global Environ. Change* 42, 331–345. doi: 10.1016/j.gloenvcha.2016.10.002

Rattalino Edreira, J. I., Andrade, J. F., Cassman, K. G., Van Ittersum, M. K., Van Loon, M. P., and Grassini, P. (2021). Spatial frameworks for robust estimation of yield gaps. *Nat. Food* 2, 773–779. doi: 10.1038/s43016-021-00365-y

Ray, D. K., Gerber, J. S., Macdonald, G. K., and West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nat. Commun.* 6, 5989. doi: 10.1038/ncomms6989

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., and Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS ONE* 14, e0217148. doi: 10.1371/journal.pone.0217148

Ridoutt, B., and Navarro Garcia, J. (2020). Cropland footprints from the perspective of productive land scarcity, malnutrition-related health impacts and biodiversity loss. *J. Clean. Prod.* 260, 121150. doi: 10.1016/j.jclepro.2020.121150

Ridoutt, B. G., Hadjikakou, M., Nolan, M., and Bryan, B. A. (2018). From water-use to water-scarcity footprinting in environmentally extended input–output analysis. *Environ. Sci. Technol.* 52, 6761–6770. doi: 10.1021/acs.est.8b00416

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S. 3rd, Lambin, E. F., et al. (2009). A safe operating space for humanity. *Nature* 461, 472–475. doi: 10.1038/461472a

Rodrigues, S., De Oliveira Silva, E., and De Brito, E. S. (2018). *Exotic Fruits: Reference Guide*. London, UK: Academic Press.

Rong, L.-B., Gong, K.-Y., Duan, F.-Y., Li, S.-K., Zhao, M., He, J., et al. (2021). Yield gap and resource utilization efficiency of three major food crops in the world – A review. *J. Integr. Agric.* 20, 349–362. doi: 10.1016/S2095-3119(20)63555-9

Rutherfurd, S. M., Fanning, A. C., Miller, B. J., and Moughan, P. J. (2014). Protein digestibility-corrected amino acid scores and digestible indispensable amino acid scores differentially describe protein quality in growing male rats. *J. Nutr.* 145, 372–379. doi: 10.3945/jn.114.195438

Sage, R. F., Peixoto, M. M., and Sage, T. L. (2013). "Photosynthesis in sugarcane," in *Sugarcane: Physiology, Biochemistry, and Functional Biology*, eds P. H. Moore and F. C. Botha, 121–154. doi: 10.1002/9781118771280.ch6

Schils, R., Olesen, J. E., Kersebaum, K.-C., Rijk, B., Oberforster, M., Kalyada, V., et al. (2018). Cereal yield gaps across Europe. *Eur. J. Agron.* 101, 109–120. doi: 10.1016/j.eja.2018.09.003

Smith, N. W., Fletcher, A. J., Dave, L. A., Hill, J. P., and Mcnabb, W. C. (2021). Use of the DELTA model to understand the food system and global nutrition. *J. Nutr.* 151, 3253–3261. doi: 10.1093/jn/nxab199

Smith, N. W., Fletcher, A. J., Hill, J. P., and Mcnabb, W. C. (2022a). Modeling the contribution of meat to global nutrient availability. *Front. Nutr.* 9, 766796. doi: 10.3389/fnut.2022.766796

Smith, N. W., Fletcher, A. J., Hill, J. P., and Mcnabb, W. C. (2022b). Modeling the contribution of milk to global nutrition. *Front. Nutr.* 8, 716100. doi: 10.3389/fnut.2021.716100

Sokolow, J., Kennedy, G., and Attwood, S. (2019). Managing crop tradeoffs: a methodology for comparing the water footprint and nutrient density of crops for food system sustainability. *J. Clean. Prod.* 225, 913–927. doi: 10.1016/j.jclepro.2019.03.056

Sustainable Nutrition Initiative® (2021). Available online at: www.sustainablenutritioninitiative.com (accessed October 29, 2021).

United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019: Data Booklet (ST/ESA/SER.A/424)*. New York, NY.

United States Department of Agriculture Economic Research Service (1992). *Agricultural Handbook Number 697, Weights, Measures, and Conversion Factors for Agricultural Commodities and Their Products*. Washington, DC: United States Department of Agriculture.

USDA (2020). *FoodData Central*. Available online at: https://fdc.nal.usda.gov/download-datasets.html (accessed August 21, 2020).

Usubiaga-Liaño, A., Mace, G. M., and Ekins, P. (2019). Limits to agricultural land for retaining acceptable levels of local biodiversity. *Nat. Sustain.* 2, 491–498. doi: 10.1038/s41893-019-0300-8

van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., and Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. *Field Crops Res.* 143, 4–17. doi: 10.1016/j.fcr.2012.09.009

von Braun, J., Afsana, K., Fresco, L., and Hassan, M. (2021). *Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit*. Rome: United Nations Food Systems Summit.

Wang, X., Dietrich, J. P., Lotze-Campen, H., Biewald, A., Stevanovi,ć, M., Bodirsky, B. L., et al. (2020). Beyond land-use intensity: assessing future global crop productivity growth under different socioeconomic pathways. *Technol. Forecast. Soc. Change* 160, 120208. doi: 10.1016/j.techfore.2020.120208

West, P. C., Gerber, J. S., Engstrom, P. M., Mueller, N. D., Brauman, K. A., Carlson, K. M., et al. (2014). Leverage points for improving global food security and the environment. *Science.* 345, 325–328. doi: 10.1126/science.1246067

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the anthropocene: the EAT-*Lancet* commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Wolfe, R. R., Baum, J. I., Starck, C., and Moughan, P. J. (2018). Factors contributing to the selection of dietary protein food sources. *Clin. Nutr.* 37, 130–138. doi: 10.1016/j.clnu.2017.11.017

Zabel, F., Delzeit, R., Schneider, J. M., Seppelt, R., Mauser, W., and Václavík, T. (2019). Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. *Nat. Commun.* 10, 2844. doi: 10.1038/s41467-019-10775-z

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., et al. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Nat. Acad. Sci. U. S. A.* 114, 9326. doi: 10.1073/pnas.1701762114

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 13 January 2023
DOI 10.3389/fsufs.2022.1072805

Check for updates

OPEN ACCESS

EDITED BY
Aida Turrini,
Independent Researcher, Rome, Italy

REVIEWED BY
Thom Huppertz,
Wageningen University and Research, Netherlands
Laurence Shalloo,
Teagasc, Ireland
Ian Enting,
Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

*CORRESPONDENCE
Frank M. Mitloehner
✉ fmmitloehner@ucdavis.edu

†PRESENT ADDRESS
Shule Liu,
State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, China

SPECIALTY SECTION
This article was submitted to Nutrition and Sustainable Diets, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 17 October 2022
ACCEPTED 23 December 2022
PUBLISHED 13 January 2023

CITATION
Pressman EM, Liu S and Mitloehner FM (2023) Methane emissions from California dairies estimated using novel climate metric Global Warming Potential Star show improved agreement with modeled warming dynamics.
Front. Sustain. Food Syst. 6:1072805.
doi: 10.3389/fsufs.2022.1072805

Methane emissions from California dairies estimated using novel climate metric Global Warming Potential Star show improved agreement with modeled warming dynamics

Eleanor M. Pressman, Shule Liu† and Frank M. Mitloehner*

Department of Animal Science, University of California, Davis, Davis, CA, United States

Introduction: Carbon dioxide (CO_2) and methane (CH_4) are two of the primary greenhouse gases (GHG) responsible for global warming. The "stock gas" CO_2 accumulates in the atmosphere even if rates of CO_2 emission decline. In contrast, the "flow gas" CH_4 has an e-folding time of about 12 years and is removed from the atmosphere in a relatively short period of time. The climate impacts of cumulative pollutants such as CO_2 and short-lived climate pollutants (SLCP) such as CH_4 are often compared using Global Warming Potential (GWP), a metric that converts non-CO_2 GHG into CO_2-equivalent emissions. However, GWP has been criticized for overestimating the heating effects of declining SLCP emissions and conversely underestimating the heating impact of increasing SLCP emissions. Accurate quantification of the temperature effects of different CH_4 emissions scenarios is particularly important to fully understanding the climate impacts of animal agriculture, whose GHG emissions are dominated by CH_4.

Methods: A modified GWP metric known as Global Warming Potential Star (GWP*) has been developed to directly quantify the relationship between SLCP emissions and temperature change, which GWP cannot do. In this California dairy sector case study, we contrasted GWP- versus GWP*-based estimates of historical warming dynamics of enteric and manure CH_4 from lactating dairy cattle. We predicted future dairy CH_4 emissions under business-as-usual and reduction scenarios and modeled the warming effects of these various emission scenarios.

Results: We found that average CO_2 warming equivalent emissions given by GWP* were greater than those given by GWP under increasing annual CH_4 emissions rates, but were lower under decreasing CH_4 emissions rates. We also found that cumulative CO_2 warming equivalent emissions given by GWP* matched modeled warming driven by decreasing CH_4 emissions more accurately than those given by GWP.

Discussion: These results suggest that GWP* may provide a more accurate tool for quantifying SLCP emissions in temperature goal and emissions reduction-specific policy contexts.

KEYWORDS

dairy production, methane, climate change, climate metrics, Global Warming Potential (GWP), enteric fermentation, manure management, short-lived climate pollutants

1. Introduction

CH_4 has the second greatest radiative forcing of all anthropogenic GHG after CO_2 (Myhre et al., 2013), and global CH_4 emissions, to which livestock is a major contributor, are responsible for about 0.5C of the 1.1C of human-forced global warming which has taken place since the year 1850 (IPCC, 2021). Enteric fermentation in the rumen of dairy cattle and their manure are major sources of biogenic methane (CH_4). Atmospheric CH_4 concentrations have increased by ∼150% since pre-industrial time (Gulev et al., 2021). Recent studies suggest that the increasing global CH_4 growth rate since 2007 has in part been driven by biogenic sources (Kai et al., 2011; Nisbet et al., 2016; Schaefer et al., 2016; Schwietzke et al., 2016).

CO_2 is known as a "cumulative pollutant" or "stock gas" due to its atmospheric lifetime that ranges from centuries to millennia (Pierrehumbert, 2014), causing it to accumulate in the atmosphere. CH_4, on the other hand, is known as a "short-lived climate pollutant" (SLCP) or "flow gas," and has an e-folding time of about 12 years. When both CO_2 and SLCP emissions increase over time, there is a short-term climate response to the change in radiative forcing ("transient warming"). When SLCP sources and sinks are equal, some long-term "equilibrium warming" will occur while the climate system equilibrates to past increases in SLCP emissions. However, after a sufficiently long period of constant emissions, there is no net accumulation in the atmosphere, radiative forcing of the atmospheric SLCP remains approximately constant, and SLCP-induced warming will stabilize. In contrast, CO_2-induced warming will always increase under positive CO_2 emissions (Cain et al., 2019). Because of its flow nature, a rapid reduction in methane emissions is one of the most feasible short-term measures to immediately curb global temperature rise (Ocko et al., 2021).

Climate metrics are used to "convert" annual emissions of various GHG that differ by atmospheric lifetime, radiative forcing, and relative magnitude of emissions into one common unit. One of the most widely used climate metrics is Global Warming Potential (GWP). GWP is constructed to estimate the radiative forcing of an emission pulse integrated over a given time horizon (often 20 or 100 years) relative to an equivalent pulse of CO_2. As constructed, GWP does not compare CO_2 to CH_4 emissions on the basis of equal radiative forcing, an accepted meaning of emissions equivalence within the radiative forcing framework, and therefore the meaning of emissions equivalence of CO_2 and CH_4 using GWP can be ambiguous (Wigley, 1998). GWP also does not relate radiative forcing to temperature change and as such is not able to capture temperature impacts within cumulative emission frameworks, although it is occasionally used for this purpose (Cui et al., 2017). GWP also does not differentiate between the contrasting behaviors of stock and flow gases, so GWP cannot capture the stable SLCP atmospheric concentrations that result from stable SLCP emissions rates. Because GWP treats SLCP like CO_2, which accumulates in the atmosphere even under stable emissions rates, GWP yields the wrong direction of temperature change under declining SLCP (Lynch et al., 2020). When CO_2 and CH_4 are compared specifically to assess their relative warming impacts on the climate, GWP overstates the warming impact of constant CH_4 emissions on global surface temperature by a factor of 3–4 over a 20-year time horizon, while understating the effect of a new CH_4 emission source by a factor of 4–5 over the 20 years following its introduction (Lynch et al., 2020). IPCC AR6 does not recommend any given emission metric because metric appropriateness depends on the purpose for which gases are being compared.

Abbreviations: E_{CH_4}, total annual CH_4 emissions (kg CH_4 per year); E_{EF}, annual enteric fermentation CH_4 emissions (kg CH_4 per year); E_{MM}, annual manure management CH_4 emissions (kg CH_4 per year); 3NOP, 3-nitrooxypropanol; AMMP, Alternative Manure Management Program; BAU, Business-as-usual; BAU EF, "business as usual" enteric fermentation scenario; CH_4, Methane; CO_2, carbon dioxide; CO_2eq, CO_2-equivalent emissions; CO_2we, CO_2-warming equivalent emissions; DDRDP, dairy digester research and development program; GHG, greenhouse gas; GWP, global warming potential; GWP*, global warming potential star; Man 40 plus BAU EF, manure management 40% reduction scenario added to the "business as usual" enteric fermentation (BAU EF) scenario; MMP, manure management practice; Pop_{dairy}, annual dairy cow population (head dairy cow); *r*, weight assigned to the rate-dependent warming effects of given SLCP in GWP*; RF_i, radiative forcing; *s*, weight assigned to the stock (long-term equilibration to past increases in forcing) contribution of given SLCP to GWP*; SLCP, short-lived climate pollutant; TCRE, transient climate response to cumulative carbon emissions; Tg, Teragrams, equivalent to million metric tons (MMT).

Because livestock GHG emissions are predominately SLCP, the warming effects of livestock agriculture can be overestimated by GWP (Persson et al., 2015). The choice of the climate metric can change the estimated climate effect of CH_4, creating uncertainties in livestock contributions to global climate change and impacts of GHG mitigation in this sector (Reisinger et al., 2013). Thus, climate metrics designed to assess SLCPs more accurately are essential to quantify the warming impacts of animal agriculture, as well as husbandry factors that control these effects over time, such as increasing efficiency and decreasing herd size. In North America, decreasing dairy herd size and increasing production efficiency may have altered relative sizes of dairy GHG sources and sinks (Capper et al., 2009; Naranjo et al., 2020). California is the largest dairy producer in the United States (USDA National Agricultural Statistics Service, 2019), and in 2017, agricultural manure management was California's second largest source of CH_4. Dairy CH_4 emissions from cow manure in California are relatively high because flush water lagoon systems are the predominate manure management system on California dairies (CARB, 2022b), and anaerobic lagoons emit the most CH_4 per head of all common manure management practices (Owen and Silver, 2015). In 2016, the California Senate passed S.B. 1383, mandating a 40% reduction of dairy manure management CH_4 emissions from 2013 levels by 2030 (Lara, 2016). Thus, using a metric that can capture the flow nature of CH_4 will gain importance as agricultural CH_4 emissions reductions strategies are implemented, particularly those targeting emissions from dairy manure.

In response to potential misrepresentations of warming effects of SLCPs by GWP, an alternate metric, Global Warming Potential Star (GWP*) has been developed. GWP* is a recent and novel application of the commonly used climate metric GWP, designed to represent the flow gas properties of SLCP rather than treating them like cumulative stock gases such as CO_2. While applying GWP to annual emissions of non-CO_2 GHG gives emissions in units of "CO_2-equivalent emissions (CO_2eq)," GWP* gives emissions in "CO_2-warming equivalent emissions (CO_2we)." GWP* relates CO_2 pulses to SLCP emissions based on approximately equivalent radiative forcing of the emissions, so CO_2we are both directly comparable to CO_2eq and can be directly related to temperature change caused by these emissions (Smith et al., 2021), unlike GWP-based CO_2eq, as discussed above (Wigley, 1998). GWP* has been demonstrated to capture dynamics of SLCP-forced warming in datasets with global emissions across many economic sectors (Lynch et al., 2020). While some authors have debated the applicability of GWP*to national and sectoral emissions (Rogelj and Schleussner, 2019), the present study is the first to use GWP* to assess dairy CH_4 warming dynamics over time and to estimate warming impacts of the mandated CH_4 mitigation efforts in California using GWP vs. GWP*. While the objective of this study was not to provide a comprehensive inventory of all CH_4 emissions from California dairy production or a cradle-to-farm gate environmental impact analysis of the California dairy production system, the present study serves as a case study to assess GWP*'s ability to represent the warming effects of sectoral SLCP under declining emissions rates. It also serves as a characterization of potential drivers of these declining dairy CH_4 emissions in California. Our objectives were to compare GWP-based CO_2-equivalent emissions vs. GWP*-based CO_2-warming equivalent emissions calculated from historical California CH_4 emissions from lactating dairy cattle and to characterize dairy CH_4 warming dynamics from 1990 to 2017. We also aimed to compare the GWP- and GWP*-based dynamics of warming effects of dairy CH_4 under future business-as-usual and reduction emissions scenarios. We hypothesized that GWP*-based cumulative CO_2-warming equivalent emissions would decline under declining CH_4 emissions and would match the dynamics of CH_4's warming effects.

2. Methods

2.1. Estimating annual methane emissions from California dairy cattle

2.1.1. Calculation of historical methane emissions from California dairy cattle (1950–2017)

We calculated annual enteric fermentation and manure management CH_4 emissions from 1950 to 2017 based on the historical California dairy cow population and US EPA Greenhouse Gas Inventory Annex 3.10 (EPA, 2013a). "Annual" emissions refer to yearly CH_4 emissions estimates that have not been converted into CO_2-equivalent or CO_2-warming equivalent emissions. Total annual CH_4 emissions from California dairies were calculated using Equation 1:

$$E_{CH_4} = E_{EF} + E_{MM}$$

Where $E_{CH_4}$is total annual CH_4 emissions (kg CH_4 per year), E_{EF} is annual enteric fermentation CH_4 emissions (kg CH_4 per year), and E_{MM} is annual manure management CH_4 emissions (kg CH_4 per year).

Annual CH_4 emissions from enteric fermentation were calculated using Equation 2:

$$E_{EF} = Pop_{dairy} \times EF_{EF}$$

Where E_{EF} is annual enteric fermentation CH_4 emissions (kg CH_4 per year), Pop_{dairy} is annual lactating dairy cow population (head dairy cow) and EF_{EF} is annual enteric fermentation emission factor (kg CH_4 per head dairy cow per year).

Dairy cow populations were derived from California Department of Food and Agriculture (CDFA) Agricultural Resource Directory reports, which provided total dairy cattle population data by county (CDFA, 2000, 2007). Annual enteric CH_4 and manure CH_4 emission factors for California dairy cattle for 2000–2017 were obtained from the California Air Resources Board (CARB) Documentation of California's Greenhouse Gas Inventory (CARB, 2022a,b). The CDFA dairy cattle population data was assumed to represent only lactating cows, so we used the enteric fermentation CH_4 emission factor for lactating cows. Enteric CH_4 emissions factors are determined based on estimated gross energy (GE) intake and CH_4 conversion rate (Y_m), which is the fraction of GE in feed converted to CH_4. GE and Y_m depend on the animal's production demands, and the characteristics of the diet fed (EPA, 2013a). Manure CH_4 emissions factors are estimated by CARB using US EPA methodology (EPA, 2013b) and are based on typical animal mass, volatile solids excretion rate (portion of organic matter in the diet that was not digested by the animal and is thus available for use by methanogenic bacteria), maximum methane producing capacity of excreted volatile solids, and nitrogen excretion rate (CARB, 2022b). Because annual emission factors were unavailable before 2000, we used the 2000 emission factors for estimates from 1950 to 1999 (Supplementary Table S1). Annual CH_4 emissions from manure management (E_{MM}, kg CH_4 per year) were calculated for *i* different manure management practices (MMP) with emission factor EF_{MMPi} (kg CH_4 per cow, Supplementary Table S2) using Equation 3:

$$E_{MM} = Pop_{dairy} \times \left(\sum_{i=1}^{i} EF_{MMP_i} \times \frac{manure_{MMP_i}}{manure_{total}} \right)$$

The proportion of manure managed by each manure management system in California and the emissions factors for each management system were obtained from the Documentation of California's Greenhouse Gas Inventory (CARB, 2022b). Because MMP proportions before year 2000 were not available from CDFA, we used the 2000 manure management practice proportions and emissions factors for 1950–1999 (Supplementary Table S3).

2.1.2. Scenario analysis of methane emissions from California dairy cattle (2018–2029)

Business-as-usual ("BAU") future emissions scenarios were generated using the same methodology. We obtained projected California dairy cattle population for 2018 to 2029 from the 2020 U.S. Agricultural Market Outlook baseline report from the Agricultural Markets and Policy (AMAP) program at the University of Missouri (FAPRI and AMAP, 2020a), which provides projected dairy cattle population assuming current policies and macroeconomic conditions remain in place (FAPRI and AMAP, 2020b). The model includes behavioral supply equations that determine milk supply *via* dairy cow inventories and milk yield per cow on a state-level basis. Milk supply equations are driven by expected net returns, which are driven by applicable federal or state policy. Demand equations are specified as a function of price, relevant substitute product prices and consumer income for various milk products (Johnson et al., 1993; Westhoff and Brown, 1999; Blayney and Normile, 2004; Fabiosa et al., 2005). These dairy cattle population projections (Supplementary Table S4) have an average annual decline rate of 0.32%, which agrees with CARB estimates of 0.5% decline in dairy cattle population from 2017 onward (CARB, 2022c). We assumed all cows in the projected dairy cattle population were lactating. We used 2017 emission factors and MMPs to calculate emissions from these dairy cows and used these emissions to extend historical 1950–2017 emissions time series to 2029 under "business-as-usual," meaning with no methane reduction programs. We used 2017 emissions factors because projected emissions factors were not available. Enteric fermentation emissions factors used by CARB were the same from 2012 to 2017 (Supplementary Table S1). Furthermore, the same emissions factors have been used up to 2020, the most recent year of the CARB GHG emissions inventory (CARB, 2022a). Because CH_4 emissions factors are estimated based on dietary and production parameters, if regionally typical diets and production remain approximately the same over time, emissions factors will remain the same from year to year. Thus, without data on future dairy cattle enteric CH_4 emissions factors, we assumed that enteric fermentation CH_4 emissions per cow would remain stable through 2029. See Section 4.4 for further exploration of this assumption.

Because AMAP provided historical cattle population data that differed slightly from the CDFA population data used for annual CH_4 emissions, enteric fermentation and manure management CH_4 emissions estimates from both differed. Linear regression was used to relate enteric fermentation and manure management CH_4 emissions estimates based on historical AMAP and CDFA population values from years for which estimates for both were available, and then future emissions estimates based on AMAP population values were adjusted according to the regression relationship (see Supplementary Table S4 for further explanation).

We generated the "Manure 40" emissions reduction scenario following California Senate Bill No. 1383 which mandates the adoption of "regulations to reduce methane emissions from livestock manure management operations and dairy manure management operations, consistent with this section and the strategy, by up to 40 percent below the dairy sector's and livestock sector's 2013 levels by 2030" (Lara, 2016). This law requires reductions in manure management emissions and does not mandate reductions in enteric fermentation emissions, so the aggregated scenario "Manure 40 plus BAU EF" refers to the manure management 40% reduction scenario added to the "business as usual" enteric fermentation (BAU EF) scenario. We assumed the 40 percent reduction goal would be met by 2030 and assumed a constant rate of reduction to meet these goals from 2018 to 2030. Such reductions could potentially be achieved by converting manure management systems from high-CH_4 emitting anaerobic lagoons to alternative management systems; see Section 2.4. Methane emissions between 2017 and 2030 were interpolated with constant reduction rate; the difference between emissions in 2017 and 2030 was divided by 13 and this step value was added to each intervening year. We also generated the "3NOP" enteric fermentation reduction scenario using reductions from use of 3-nitroxypropanol (3NOP), a synthetic feed additive that inhibits the enzyme that catalyzes the methane-forming step in the rumen (Duin et al., 2016). Maximum reductions in enteric CH_4 emissions from dairy cattle supplemented with 3NOP vary across studies and may depend on animal factors and basal diet (Dijkstra et al., 2018). In the only dairy 3-NOP study conducted in California, maximum net reductions using 3NOP were 11.7% (Feng and Kebreab, 2020). We assumed this reduction would be achieved by 2030 and interpolated emissions of intervening years using the same method as manure management emissions. The "Manure 40 plus 3NOP" refers to the 40% manure management reduction scenario plus the 11.7% "3NOP" enteric fermentation reduction scenario.

2.2. Calculating CO_2-equivalent emissions using GWP and CO_2-warming equivalent emissions using GWP*

2.2.1. Converting annual CH_4 emissions to CO_2-equivalent emissions using GWP

In the following section, we describe how GWP and GWP* were used to calculate CO_2-equivalent (CO_2eq) or CO_2-warming equivalent emissions (CO_2we), respectively. GWP is generated by integrating the radiative forcing (the change in incoming and outgoing energy of the Earth system actuated by a given GHG) of a single emission ("pulse") of that GHG over a given time horizon H, divided by the same quantity for CO_2. The GWP of gas i with radiative forcing (RF_i) by Equation 4:

$$GWP_i = \frac{\int_0^H RF_i(t)dt}{\int_0^H RF_{CO_2}(t)dt} \text{ (Solomon et al., 2007).}$$

GWP is used to convert other GHGs into CO_2eq, defined for a gas i as emissions per year (E_i) multiplied by GWP. CO_2eq are defined by Equation 5:

$$CO_2eq = E_i \times GWP_i.$$

Where CO_2eq are given in teragrams per year (Tg, equivalent to million metric tons, MMT) of CO_2eq emissions (TgCO_2eq/year) and E_i is given in Tg per year of gas E_i.

We used a 100-year time horizon for both GWP and GWP*. We used the GWP_{100}value of CH_4 from the IPCC 4th Assessment Report (Solomon et al., 2007), 25, which is consistent with the CARB GHG Current California Emission Inventory Data (CARB, 2022a,b).

2.2.2. Converting annual CH_4 emissions to CO_2-warming equivalent emissions using GWP*

We converted the CH_4 emissions into CO_2-warming equivalent emissions (CO_2we) using GWP*. GWP* considers an increase in the emission rate of an SLCP to be equivalent to a one-off pulse emission of CO_2 (Allen et al., 2018) and is used to convert SLCP emissions to CO_2we, which are directly comparable to CO_2eq (Allen et al., 2018). Under GWP*, CO_2we are defined by Equation 6:

$$CO_2we = GWP_i \times \left(r \times \frac{dE_i}{dt} \times H + s \times E_i \right)$$

where CO_2we are given in Tg of CO_2-warming equivalent emissions per year (TgCO_2we per year), GWP_i is the conventional GWP for gas i over time-horizon H, dE_i the change in the emission rate of gas i over the preceding dt years in Tg E_i per year, E_i the emissions of gas i in that year in Tg E_i per year, and r and s the weights assigned to the rate and stock contributions, respectively (Cain et al., 2019). r controls the rate-dependent warming effects of SLCP and s controls the long-term equilibration to past increases in forcing. We used $r = 0.75$ and $s = 0.25$ according to Cain et al. (2019), where these coefficients are the mean of coefficients determined when regressing different cumulative CH_4 emissions scenarios against modeled warming of these emission scenarios. We used a dt of 20 years according to Allen et al. (2018). Using $r = 0.75$, $s = 0.25$, $H = 100$, and $dt = 20$, the GWP* equation can be simplified further to Equation 7 (Lynch et al., 2020):

$$CO_2we = \left(4 \times E_{i_t} - 3.75 \times E_{i_{t-20}}\right) \times GWP_i.$$

We used this equation for conversion of annual CH_4 emissions into CO_2we emissions. It should be noted that the definition of GWP*-based CO_2-warming equivalent emissions has since been updated to include a scaling factor g ($g = 1.13$) to directly relate the radiative forcing of CO_2 and SLCP emissions without reference to temperature response, but the authors suggest that scaling factors of order 10% may not be necessary given their additional complexity (Smith et al., 2021).

2.3. Modeling warming responses to estimated methane emissions

We used the FaIR (Finite-Amplitude Impulse Response) v1.3 climate-carbon-cycle model to simulate the warming effects of the annual CH_4 emissions (Millar et al., 2017; Smith et al., 2018). It should be noted that this FaIR model is not the same as climate policy decision-support tool FAIR model (den Elzen and Lucas, 2005). Following Lynch et al. (2020), we forced the model with the complete RCP4.5 emissions scenario (Smith and Wigley, 2006; Wise et al., 2009; Lamarque et al., 2010), then forced the model with these same emissions, plus CH_4 emissions from each scenario. We then subtracted the first warming time-series from the second to generate the warming response to each emissions scenario. We used default FaIR parameters and set volcanic and solar forcing to zero and efficacies for each forcing agent compared to CO_2 to one, except black carbon, which was set to three (Bond et al., 2013).

2.4. Identifying husbandry factors driving declining dairy CH_4 emissions

Given the importance of capturing CH_4's flow nature especially under declining emissions rates, we conducted a separate analysis from that described in Sections 2.1–2.3 to determine if California dairy background CH_4 emissions are declining and identify husbandry factors driving potential decline. Production data (dairy cattle populations and per capita dairy cow milk production) were obtained from the USDA QuickStats database (USDA National Agricultural Statistics Service, 2019). Manure management CH_4 reductions from emissions reduction programs were obtained from the CDFA Dairy Digester Research and Development Program (DDRDP) and Alternative Manure Management Program (AMMP) websites (CDFA, 2022a,b). To investigate the impact of these programs, we estimated what CH_4 emissions would have hypothetically been without these programs. These estimates comprised a separate analysis and were not used to investigate emission dynamics or to force the climate model but were only used to assess the impact of various factors that may have led to reduced CH_4 emissions in California. To estimate hypothetical emissions without DDRDP and AMMP, annual emission reductions provided by CDFA were converted from Tg CO_2eq to Tg CH_4 using the AR4 GWP100 of CH_4 (25) and were added cumulatively to the estimated total annual dairy CH_4 emissions of the reduction year. For example, the 2016 estimated emissions reductions were added to 2016 CH_4 emissions to estimate hypothetical 2016 emissions without DDRDP or AMMP reductions, and 2016 plus 2017 estimated emissions reductions were added to 2017 CH_4 emissions to estimate putative 2017 emissions without DDRDP or AMMP reductions, etc. Although DDRDP and AMMP reductions were available to 2019, historical CH_4 emissions were only available to 2017, so the 2017 CH_4 emissions were used for all years following 2017. Statistical analysis for the entire study was conducted in R (R Core Team, 2020).

3. Results

3.1. Comparison of average annual CO_2eq and CO_2we from each scenario

We converted historical annual CH_4 emissions, a future business-as-usual CH_4 emission scenario, and two future reduction CH_4 emissions scenarios from California dairy cattle into CO_2-equivalent emissions or CO_2-warming equivalent emissions using the two different metrics GWP and GWP*, respectively. We used the conventional GWP and the novel GWP*, which is a modification of GWP that contains a term for the change in the rate of emission of SLCP such as methane. GWP gives CO_2-equivalent emissions (CO_2eq), while GWP* gives CO_2-warming equivalent emissions (CO_2we). "Total dairy emissions" were calculated using Equation 1. We used an emission-based climate model to predict the warming impacts of each annual CH_4 emissions scenario to compare the warming profiles against the dynamics of CO_2-equivalent emissions calculated by each metric for each scenario.

We first investigated if GWP-based emissions estimates (CO_2eq) and GWP*-based emissions estimates (CO_2we) differed significantly in each emissions scenario. GWP-based CO_2eq emissions and GWP*-based CO_2we were calculated from identical annual "background" CH_4 emissions, but all average CO_2eq and CO_2we under the same reduction scenarios differed significantly (Figure 1). Average GWP*-based estimates for the historical period were larger than GWP-based estimates. In this historical period, there are 37% more annual CO_2-warming equivalent CH_4 emissions when calculated using GWP* than when calculated using GWP (Figure 1).

In the BAU manure and enteric CH_4 scenario and 40% reduction of manure management CH_4 with BAU enteric CH_4 scenario, CO_2we were lower than CO_2eq (Figure 1). Furthermore, under 40% reduction of future annual manure management CH_4 emissions in the "Man. 40 plus BAU EF CO2eq" reduction scenario, some annual CO_2we are negative, while CO_2eq were never negative. Under 40% reduction of future annual manure management CH_4 emissions with maximum 3NOP reductions, the average of *all* annual CO_2we were negative, while again CO_2eq were never negative (Figure 1).

CO_2eq are less variable than GWP*-based CO_2 warming equivalent emissions, particularly in the future BAU scenario, where CO_2eq are approximately constant. GWP*-derived emissions are more variable because they are calculated by

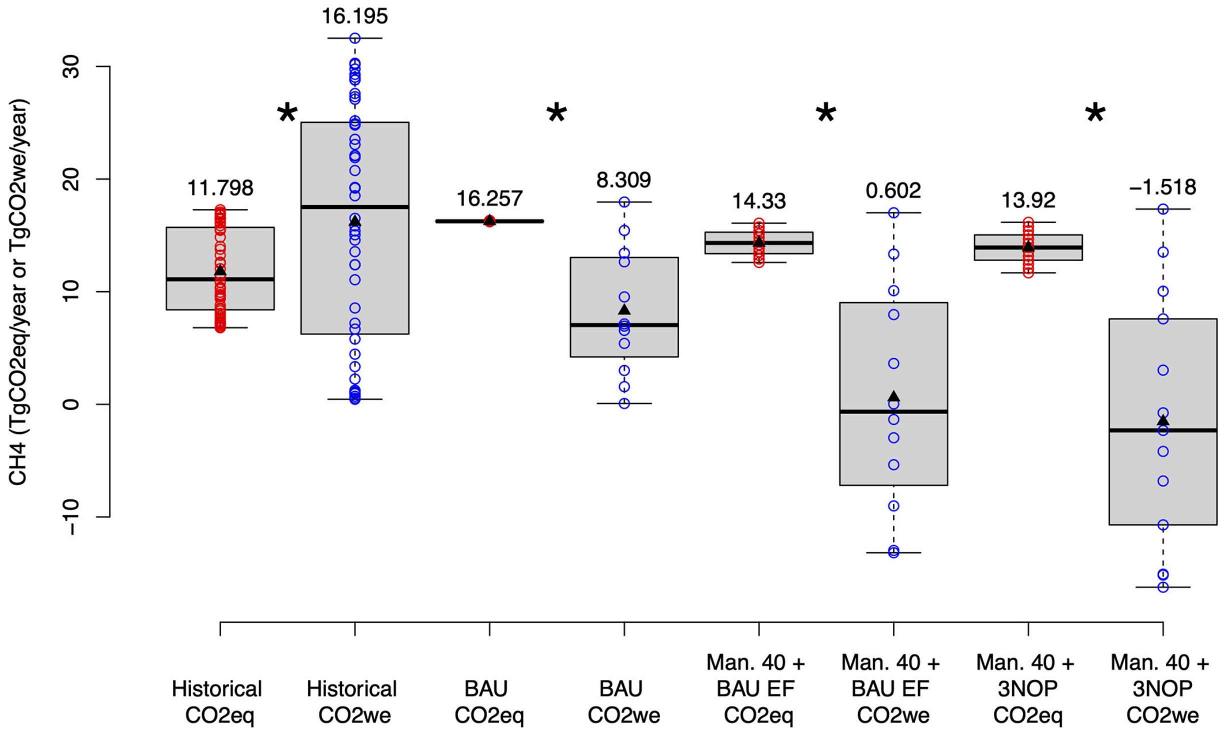


FIGURE 1
Comparison of annual total dairy CH_4 emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively. The *x*-axis shows each emission scenario and which metric was used. Historical data is from 1950 to 2017. The BAU scenario and Manure 40 plus BAU EF ("Man. 40 + BAU EF") are from 2018 to 2029. The Manure 40 plus 3NOP ("Man. 40 + 3NOP") is from 2018 to 2030. The *y*-axis denotes CO_2-equivalent or CO_2-warming equivalent emissions, respectively, computed from CH_4 emissions; GWP gives "CO_2eq" emissions, while GWP* gives "CO_2we." Each circle represents an observation of annual emissions rate from each time period and emissions scenario. Red open circles are data points calculated using GWP; blue open circles are data points calculated using GWP*. Values above boxes are mean values; means are denoted as black triangles on plot. Asterisks between plots indicate means of GWP- and GWP*-based emissions differ significantly (paired student's *t*-test, $p < 0.05$).

subtracting the current year emissions rate from that of 20 years previously, which is particularly variable under reduction scenarios where future emissions are reduced relative to those in the historical period.

3.2. Comparison of cumulative CO_2eq and CO_2we with modeled warming over historical period (1950–2017)

Because cumulative CO_2 emissions and temperature change are linearly related (Allen et al., 2009; Matthews et al., 2009), the dynamics of the two should be similar over time and the warming profile serves as a means of evaluating GWP and GWP*. We next examined the relationship between "background" annual CH_4 emissions, cumulative GWP- and GWP*-based emissions estimates, and modeled warming, in each emissions scenario, to evaluate these two metrics.

In the historical period, annual CH_4 emissions increased from 1950 to 2008, but slightly decreased from 2008 to 2017 (Figure 2A). During the increasing annual CH_4 emissions, CO_2we were higher than CO_2eq (Figure 2B). Under decreasing annual CH_4 emissions from 2008 to 2017, however, annual CO_2we decreased, while annual CO_2eq increased. Because annual CO_2we decreased from 2008 to 2017, when each annual estimate was added up to give cumulative emissions, cumulative CO_2we did not increase linearly from 2008 to 2017 but instead, the rate of increase of cumulative emissions slowed, decreasing the slope of the line (Figure 2C). In contrast, because annual CO_2eq increased over the entire historical period, cumulative CO_2eq increased linearly (Figure 2C). The slope of the line representing warming caused by annual CH_4 emissions also decreased from 2008 to 2017 (Figure 2C). As noted above, the dynamics of cumulative CO_2-equivalent emissions and warming forced by these emissions should be similar over time, so in this scenario, the decreasing slope of the warming and cumulative GWP* lines suggests that they may be in better agreement than GWP and the warming line.

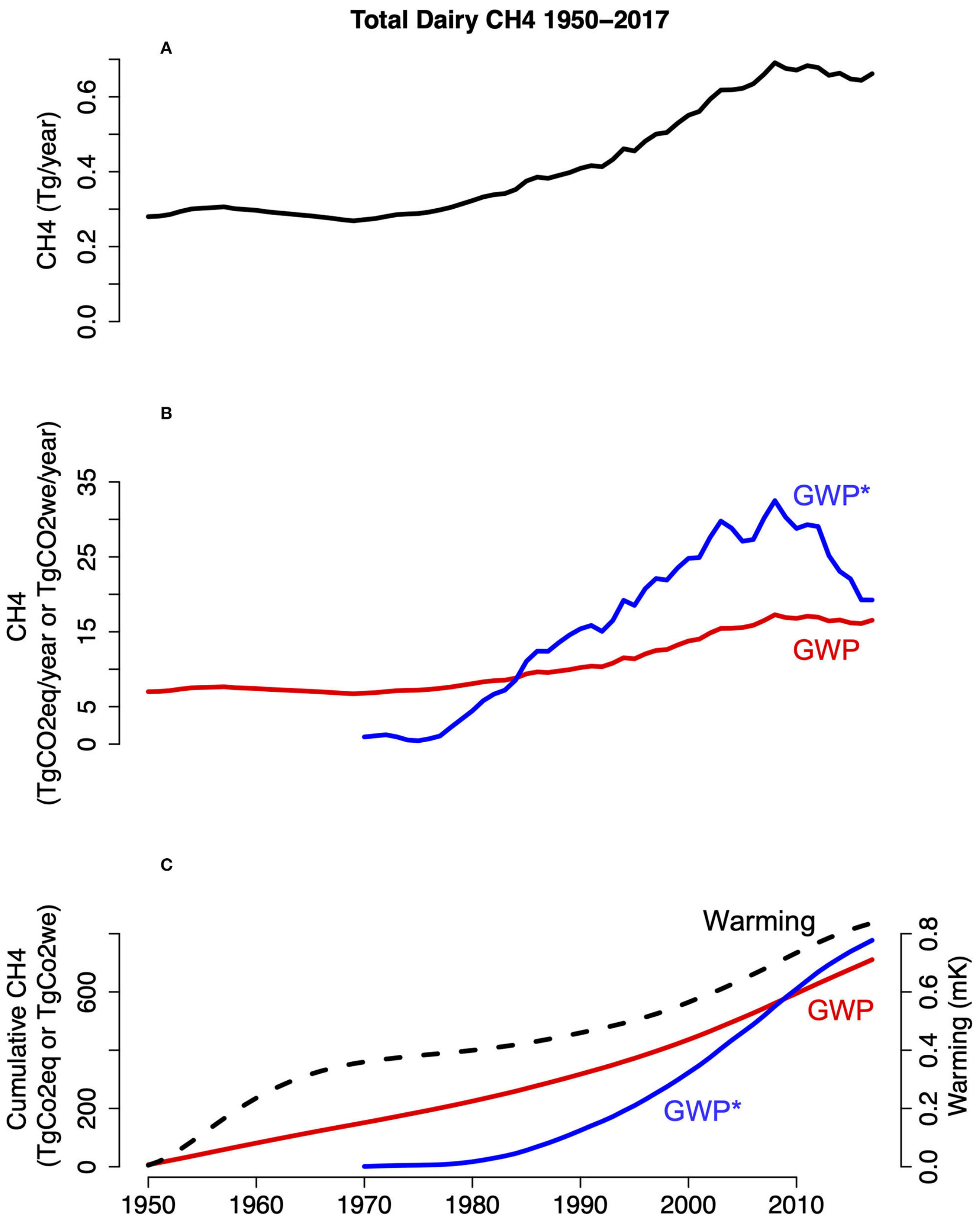


FIGURE 2
California 1950–2017 total historical CH_4 emissions, comparison of these emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively, and cumulative CO_2eq and CO_2we with emissions-forced warming. The *x*-axis represents years and the *y*-axis represents annual CH_4 emissions **(A)**, annual CO_2eq or CO_2we **(B)**, or cumulative CO_2eq or CO_2we **(C)**. CO_2we are represented in **(B, C)** by the blue solid line ("GWP*"), GWP-based CO_2eq are represented by the red solid line ("GWP"), and temperature is given in **(C)** by the dashed black line ("Warming"). The temperature axis in **(C)** is scaled by 0.001 mK/TgCO_2, or 1 K/TtCO_2. The scaling factor that relates cumulative CO_2 emissions to temperature change is known as transient climate response to cumulative carbon emissions (TCRE). The scaling factor here (approximate TCRE) exceeds the IPCC likely range, likely due to a large increase in annual CH_4 emissions in the 1950s leading to a larger GWP of CH_4 in this period (see Section 4). This large GWP may be responsible for the "bulge" in warming between 1950 and 1990 **(C)**.

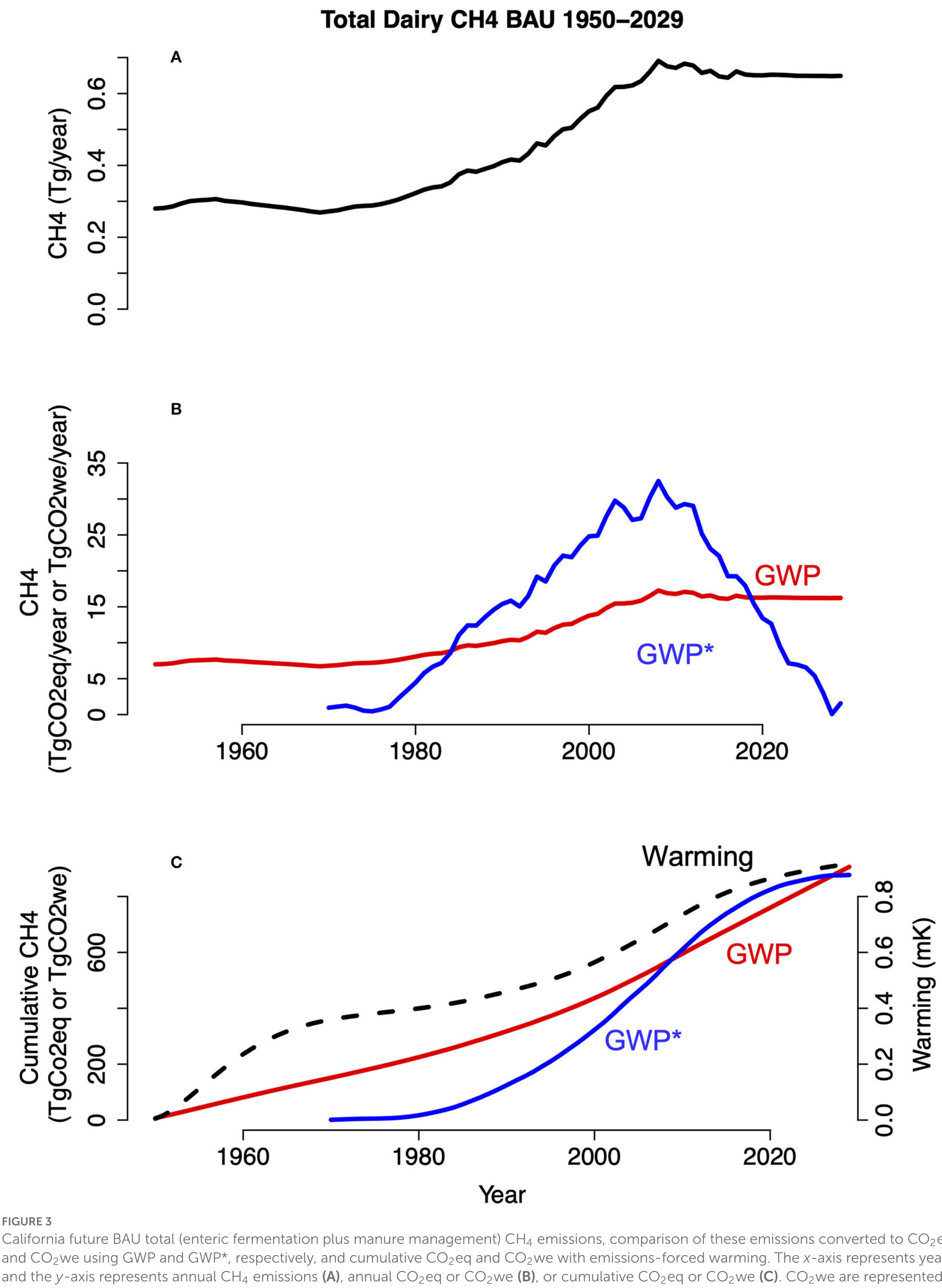


FIGURE 3
California future BAU total (enteric fermentation plus manure management) CH_4 emissions, comparison of these emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively, and cumulative CO_2eq and CO_2we with emissions-forced warming. The *x*-axis represents years and the *y*-axis represents annual CH_4 emissions **(A)**, annual CO_2eq or CO_2we **(B)**, or cumulative CO_2eq or CO_2we **(C)**. CO_2we are represented in **(B, C)** by the blue solid line ("GWP*"), CO_2eq are represented by the red solid line ("GWP"), and temperature is given in **(C)** by the dashed black line ("Warming"). The temperature axis **(C)** is scaled by 0.001 mK/TgCO_2, or 1 K/TtCO_2, as in Figure 2.

3.3. Comparison of cumulative CO_2eq and CO_2we with modeled warming over BAU scenario (2017–2029)

In the BAU manure and enteric CH_4 emissions scenario, annual background CH_4 emissions from 2008 to 2029 were approximately constant (Figure 3A). Under constant annual CH_4 emissions, CO_2we declined, while CO_2eq were approximately constant (Figure 3B).

Because annual CO_2we decreased from 2008 to 2017, when each annual estimate was added up to give cumulative emissions, cumulative CO_2we did not increase linearly from 2008 to 2017 but instead, the rate of increase of cumulative emissions slowed and the line representing CO_2we "flattens out," or stops accumulating (Figure 3C). In contrast, because annual CO_2eq increased over the entire historical period, cumulative CO_2eq increased linearly (Figure 3C).

Because GWP*-based cumulative CO_2we did not increase under constant annual CH_4 emissions, they fit the warming better than CO_2eq, like in the historical period, but the difference in the near-constant BAU scenario is easier to see. GWP-derived estimates did not match warming dynamics because CO_2eq continued to increase linearly under constant annual CH_4 emissions.

3.4. Comparison of cumulative CO_2eq and CO_2we with modeled warming over 40% manure CH_4 emissions reduction plus BAU enteric CH_4 emissions scenario (2017–2029)

In the "Manure 40 plus BAU EF" reduction scenario, manure CH_4 is reduced by 40% from 2017 to 2029, while enteric CH_4 follows a "business as usual" projection. In this moderate reduction scenario, annual background manure management and total CH_4 emissions declined from 2017 to 2029 (Figures 4A, B). Under declining CH_4 emissions from 2017 to 2029, both manure management and total CO_2we declined, even reaching negative annual emissions rates (Figures 4C, D). CO_2eq also declined under declining annual CH_4 emissions, but did not reach negative emissions rates.

When each annual CO_2we emissions estimate was added up to give cumulative emissions, because some annual emissions rates were negative, cumulative CO_2we *decreased* from 2017 to 2029 (Figures 4E, F). In contrast, GWP-based cumulative CO_2eq continued to increase under declining future annual CH_4 emissions (Figures 4C, D). Warming forced by declining annual CH_4 emissions also declined, so cumulative GWP*-based CO_2we reflected these dynamics better than cumulative GWP-based CO_2eq.

3.5. Comparison of cumulative CO_2eq and CO_2we with modeled warming over 40% manure CH_4 emissions reduction plus reduced enteric CH_4 emissions scenario (2017–2030)

The "Manure 40 plus 3NOP" reduction scenario represents a more ambitious reduction scenario than "Manure 40 plus BAU EF," because it incorporates reductions in both manure and enteric CH_4. In this high reduction scenario, future annual enteric fermentation and total CH_4 emissions declined from 2017 to 2030 (Figures 5A, B). This decline also occurred in the "Manure 40 plus BAU EF," but the decrease is sharper in the "Manure 40 plus 3NOP" scenario. Under declining future CH_4 emissions, both enteric fermentation and total CO_2we declined and reached negative annual emissions rates (Figures 5C, D). CO_2eq also declined under declining annual CH_4 emissions, but did not reach negative emissions rates.

Again, when each annual CO_2we emissions estimate was added up to give cumulative emissions, because some annual emissions rates were negative, cumulative CO_2we *decreased* from 2017 to 2030 (Figures 5E, F). In contrast, GWP-based cumulative CO_2eq continued to increase under declining future annual CH_4 emissions (Figures 5C, D). Warming forced by declining annual CH_4 emissions also declined, so cumulative GWP*-based CO_2we reflected these dynamics better than cumulative GWP-based CO_2eq. Because the rate of decline of emissions is greatest in this scenario, the difference between GWP- and GWP*-based emissions estimates and their agreement with warming dynamics is most clear in this scenario.

3.6. Relationship between cumulative CO_2eq and CO_2we from all scenarios and modeled warming

Figure 6 plots cumulative CO_2eq and CO_2we from historical, BAU, and reductions scenarios, respectively, against modeled warming. This plot shows the same information as previous plots, but allows us to directly visualize the relationship between cumulative CO_2 emissions and temperature change in this study. We expect cumulative CO_2 or CO_2-equivalent emissions and temperature to be linearly related, as this is a well-established physical relationship. In the historical period, annual background CH_4 emissions increased over time, and so both cumulative GWP-based CO_2eq and GWP*-based CO_2we increased, as discussed in Section 3.2. Modeled temperature also increased over time in the historical periods, as expected given the linear relationship between cumulative CO_2 emissions and temperature change (Figure 6A).

Under the "Manure 40 plus 3NOP" future reductions scenario, annual background CH_4 emissions decrease over

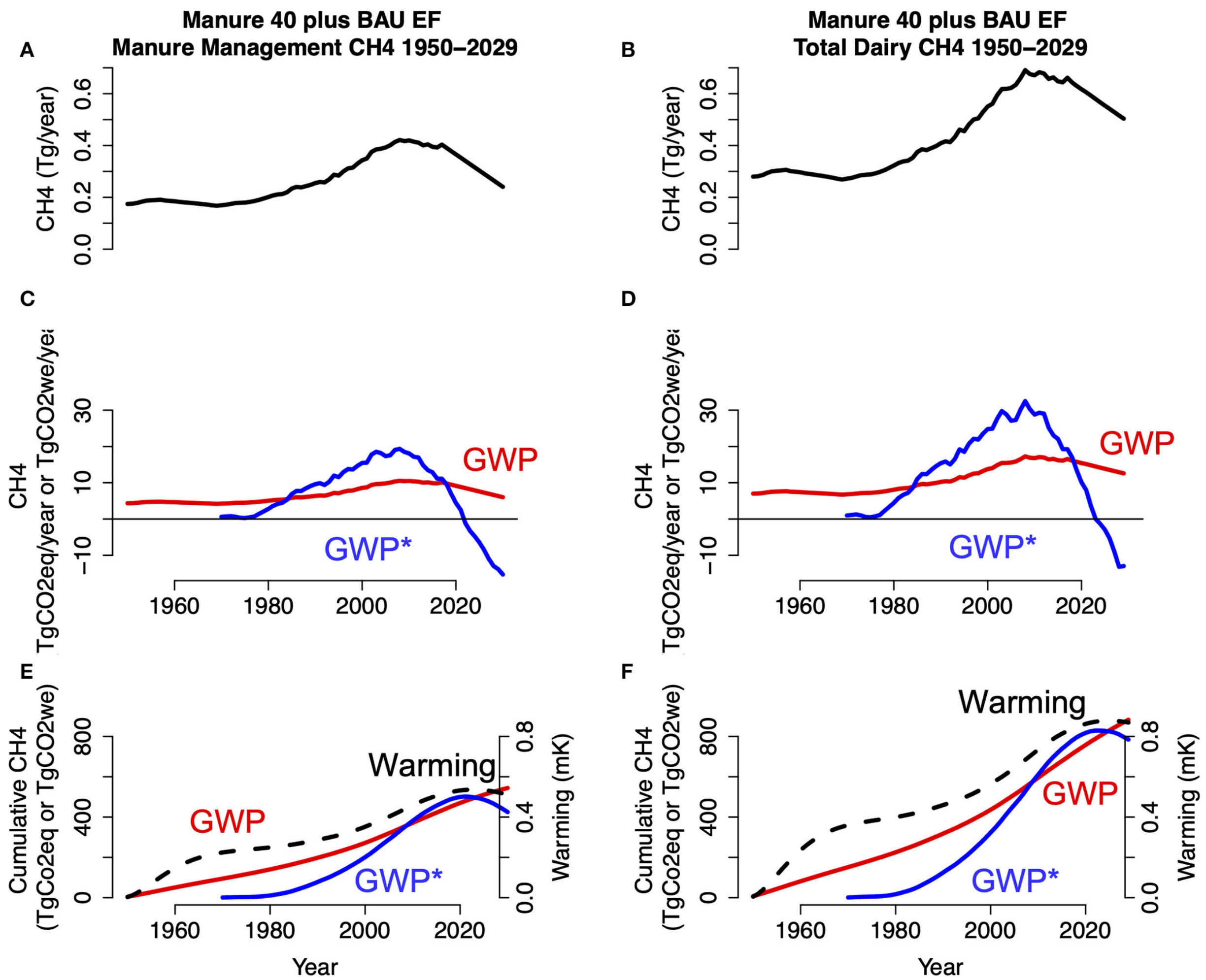


FIGURE 4
California future manure management and total "Manure 40 plus BAU EF" reduction scenario CH_4 emissions, comparison of these emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively, and cumulative CO_2eq and CO_2we with emissions-forced warming. The *x*-axis represents years, and the *y*-axis represents annual CH_4 emissions **(A, B)**, annual CO_2eq or CO_2we **(C, D)**, and cumulative CO_2eq or CO_2we **(E, F)**. Manure management CH_4 is presented in **(A, C, E)**, and total dairy CH_4 is given by **(B, D, F)**. CO_2we are represented in **(C–F)** by the blue solid line ("GWP*"), CO_2eq are represented in **(C–F)** by the red solid line ("GWP"), and temperature is given in **(E, F)** by the dashed black line ("Warming"). The temperature axis **(C)** is scaled by 0.001 mK/$TgCO_2$, or 1 K/$TtCO_2$, as in previous figures. The horizontal black line in **(C, D)** is at $y = 0$.

time. As discussed in Section 3.5, in this scenario, cumulative CO_2eq continue to increase in this scenario while cumulative CO_2we increased until 2017, then decreased. Temperature change forced by the background CH_4 emissions also increased until 2017, then decreased. That cumulative CO_2eq continue to increase implies that increasing cumulative emissions can cause decrease warming, which is an unphysical relationship (Figure 6B). In contrast, the relationship between cumulative CO_2we and warming is always linear—when cumulative CO_2we increase, warming is also increasing, but when CO_2we begin to decrease, warming also decreases and the blue line "turns back" on itself. This plot thus gives another visualization of results from previous plots, which are that CO_2we matched the dynamics of warming from declining background CH_4 emissions better than GWP-based emissions, or in other words can capture the physical relationship linking cumulative CO_2 emissions and temperature change that GWP does not.

In the manure and enteric CH_4 BAU scenario, annual background CH_4 emissions are approximately constant, as discussed in Section 3.3. Warming forced by these emissions "flatten out" during the period of constant background emissions. In this scenario, cumulative CO_2we "flatten out" and stop accumulating, while cumulative CO_2eq continue to increase. When cumulative CO_2eq are plotted against temperature change, while warming stays approximately constant, cumulative emissions continue to increase, implying that constant cumulative emissions can cause constant warming, which is an unphysical relationship (Figure 6B). In contrast, cumulative CO_2we stop increasing under these near-constant background emissions, almost "turning back"

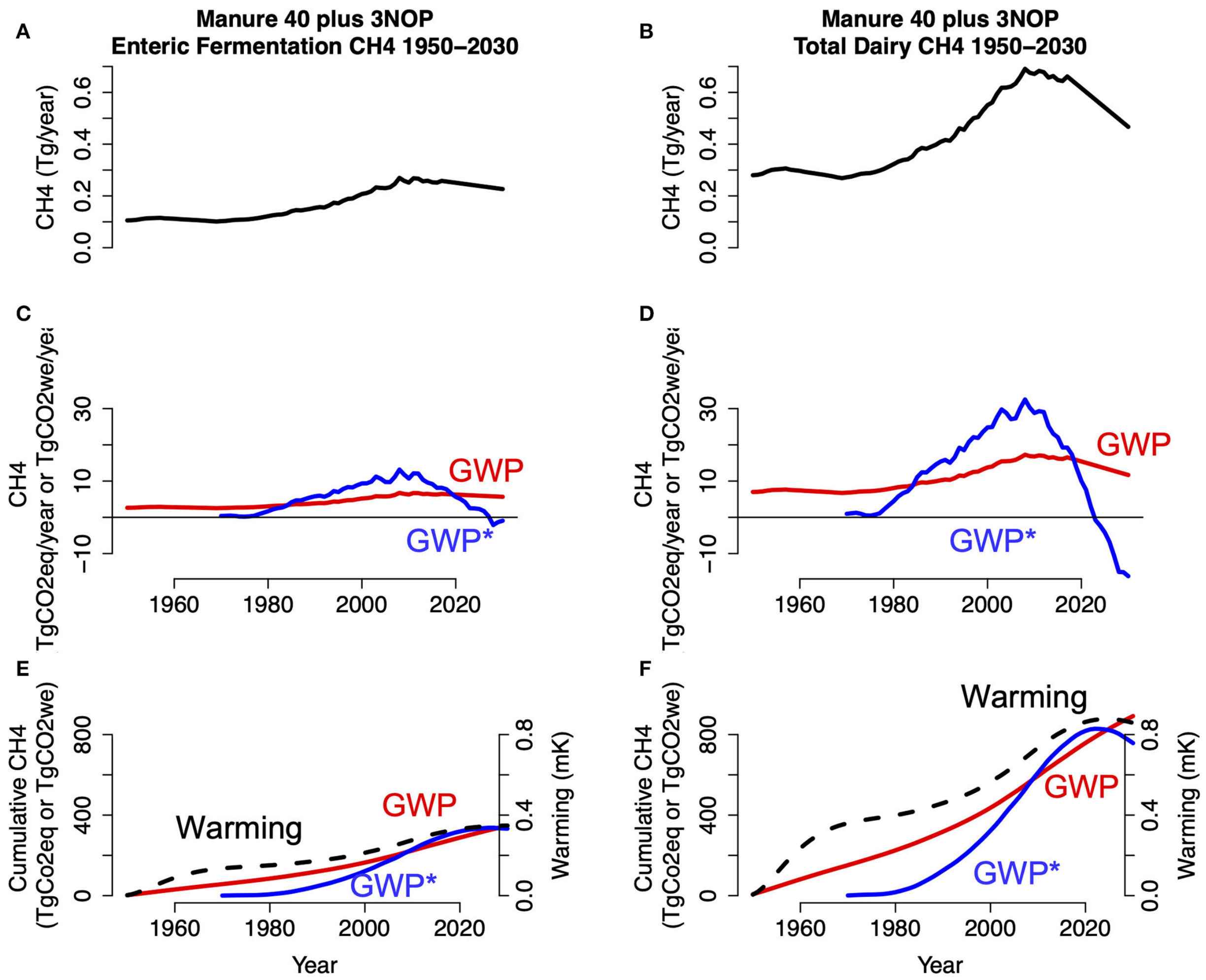


FIGURE 5
California future enteric fermentation and total "Manure 40 plus 3NOP" reduction scenario CH_4 emissions, comparison of these emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively, and cumulative CO_2eq and CO_2we with emissions-forced warming. The *x*-axis represents years, and the *y*-axis represents annual CH_4 emissions **(A, B)**, annual CO_2eq or CO_2we **(C, D)**, or cumulative CO_2eq or CO_2we **(E, F)**. Enteric fermentation estimates are given by **(A, C, E)**, and total dairy emissions are given by **(B, D, F)**. CO_2we are represented in **(C–F)** by the blue solid line ("GWP*), CO_2eq are represented in **(C–F)** by the red solid line ("GWP"), and temperature is given in **(E, F)** by the dashed black line ("Warming"). The temperature axis **(C)** is scaled by 0.001 mK/$TgCO_2$, or 1 K/$TtCO_2$, as in previous figures. The horizontal black line in **(C, D)** is at $y = 0$.

like in Panel C and again showing that GWP*-based emissions dynamics match warming dynamics better under constant background emissions.

3.7. Husbandry factors driving declining California dairy CH_4 emissions from 2008 to 2017

Given the importance of capturing CH_4's flow nature especially under declining emissions rates, we conducted a separate analysis from the hypothetical scenarios, including hypothetical reductions scenarios, giving the results described in Sections 3.1–3.6. We conducted this separate analysis to determine if California dairy background CH_4 emissions are in fact declining and, if so, to identify husbandry factors driving the decline in emissions. Historical annual CH_4 emissions decrease from 2008 to 2017 after a peak in 2008 (Figures 7A, B). This decrease in CH_4 emissions is likely a result of decreasing California dairy cattle populations, which peaked in 2009 (Figures 7A, C). Because CH_4 emissions depend heavily on cattle population, this decreasing population from 2009 to 2019 is likely driving decreasing CH_4 emissions. This decreasing cattle population in turn may be driven by increasing

10.3389/fsufs.2022.1072805

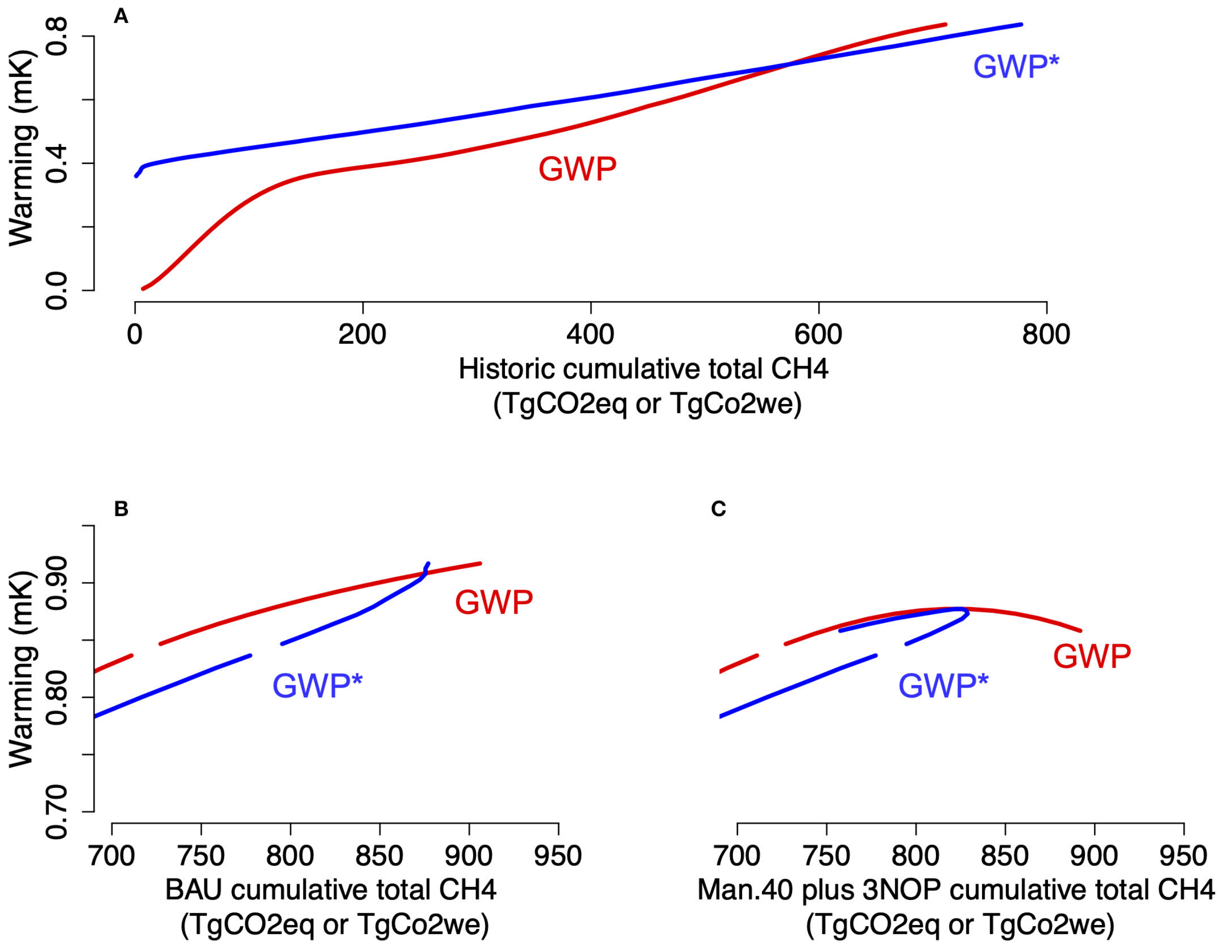


FIGURE 6
The relationship of CO_2eq and CO_2we with modeled warming response to these emissions. The *x*-axis shows cumulative CO_2eq calculated using GWP in red ("GWP"), or CO_2we calculated using GWP* in blue ("GWP*"). The y axis shows warming from annual CH_4. **(A)** Shows data from the historical (1950–2017) period. The slope of the line of cumulative CO_2 emissions and temperature change is approximately TCRE. **(B)** Shows future (2018–2029) BAU emissions, while **(C)** shows future (2018–2030) "Manure 40 plus 3NOP" reduction scenario emissions. Lines are broken between historical and future data.

per capita milk production (Figure 7C), as per capita milk production has increased from 2009 to 2019 and per capita milk production and dairy population are negatively correlated from 2009 to 2019 (data not shown). Manure management CH_4 emissions have also been reduced by CDFA Dairy Digester Research and Development Program (DDRDP) since 2015 and Alternate Manure Management Program (AMMP) since 2017. The majority of reductions are due to DDRDP. These programs provide estimates of annual CH_4 reductions due to program implementation, which have been added to historical annual CH_4 emissions to plot putative emissions without these programs. Decreases in total CH_4 since 2008 have been driven by decreasing population and decreased CH_4 from manure management due to CDFA programs (Figure 7B).

4. Discussion

4.1. Application of GWP* to CH_4 emissions from livestock agriculture

Previous studies have applied GWP* to large, RCP-based CH_4 datasets (Cain et al., 2019; Lynch et al., 2020). Ours builds upon this work and is the first to our knowledge to apply GWP* to sectoral emissions from a North American animal production system, and thus serves as case study for the application of GWP* to smaller industry- and locale-specific CH_4 emissions data. Previous authors have debated GWP*'s applicability to sectoral and national emissions, which will be discussed further here. Nonetheless, previous authors have applied GWP* and other alternative GHG metrics to local

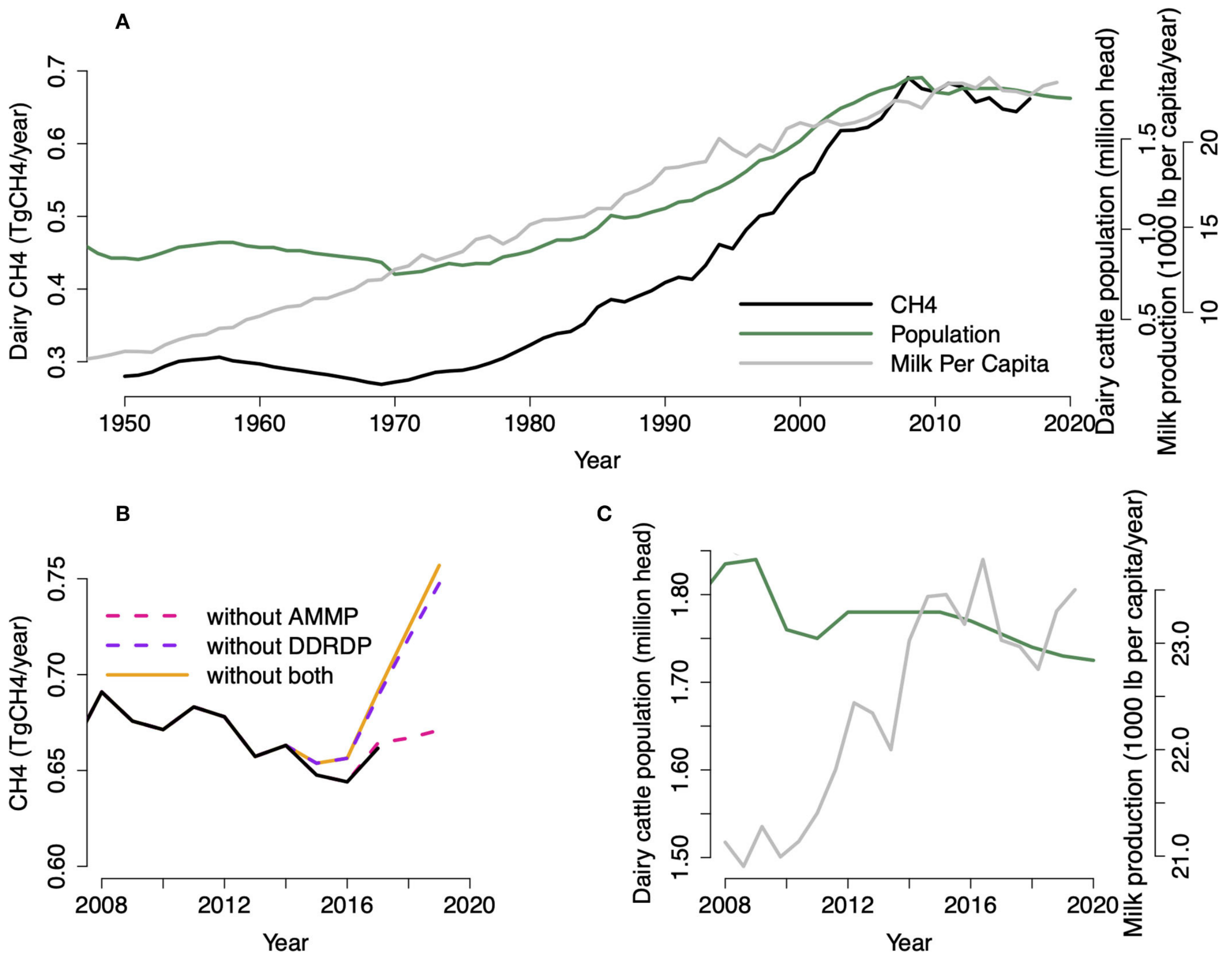


FIGURE 7
Mechanisms of decreasing CH_4 emissions since 2008 include decreasing dairy herd size, increasing per capita production, and manure management CH_4 reductions programs. In **(A–C)**, the *x*-axis shows years; in **(A)** the entire historical time series is shown (1950–2017), while in **(B, C)**, only 2008–2017 are shown. In **(A, B)**, the *y*-axis is annual total dairy CH_4 emissions, but in **(B)** the *y*-axis does not begin at zero in order to provide a close-up view of CH_4 dynamics from 2008 to 2017. In **(A)**, the right y axis shows per capita milk production and cattle population. **(B)** Shows hypothetical estimates of annual CH_4 reductions due to DDRDP and AMMP program implementation, which has been added to historical CH_4 emissions to plot putative emissions without these programs. The *y*-axis of **(C)** shows cattle population and the right y axis shows per capita milk production.

agricultural sectors, including Australian beef feedlots (Ridoutt et al., 2022), Australian sheep meat production (Ridoutt, 2021a), Australian livestock production (Ridoutt, 2021b), and Austrian dairy production (Hörtenhuber et al., 2022). Similar to reductions scenarios in our study, Ridoutt and coauthors found larger potential GHG reduction benefits from supplementing Australian beef steers with enteric CH_4-inhibiting macroalgae *Asparagopsis taxiformis* when emissions were assessed using GWP* rather than GWP (Ridoutt et al., 2022). Similarly to our study, Hörtenhuber and coauthors found that decreasing lactating dairy cattle population due to improved production efficiency resulted in strong sectoral emission reductions from dairy production, which were greater when assessed with GWP* than with GWP_{100} (Hörtenhuber et al., 2022). In Australian livestock industries where CH_4 emissions increased from 1990 to 2018 (beef, pork, and dairy production), emissions from the beef cattle, pig meat and milk production industries assessed using GWP* contributed to climate warming less than when assessed with the GWP_{100} climate metric (Ridoutt, 2021b). While increasing background emissions in Australia from 1990 to 2018 are similar to our "historical" scenario, we found that under increasing background emissions, GWP*-based emissions estimates were greater than those given by GWP. This discrepancy may be because the authors used total GHG emissions, not only CH_4, in their analysis. It may also result from annual Australian CH_4 emissions increasing by less than needed for CO_2we to exceed CO_2eq, 1% per year. In this study, dairy CH_4 emissions were 214 kt in 1990 and 275 kt in 2018, which gives an approximate rate of increase of 1% per year. Beef CH_4 emissions were 1,252 kt in 1990 and 1,421 in 2018, which gives an approximate rate of increase of 0.4% per year, below the approximate threshold for CO_2we greater than CO_2eq, discussed further immediately below.

4.2. Rate of change of CH_4 emissions leading to zero CO_2we emissions

Because of how the metrics are constructed, under a positive rate of change, CO_2we are greater than GWP-based CO_2-equivalent emissions when the rate of change of emissions is >1% per year. In our historical CH_4 emissions dataset, annual CH_4 emissions increased over time, leading to continuously increasing CO_2we. CO_2we are weighted heavily under increasing annual CH_4 emissions because CH_4 is being added to the atmosphere and CH_4 has a stronger radiative forcing per unit mass than CO_2 (Fuglestvedt et al., 2003). When CO_2eq are set equal to CO_2we (Equations 5 and 6), we see that $\frac{dE_i}{dt}$ is equal to E_i when $\frac{dE_i}{dt} = 0.01 \times E_i$. Thus, CO_2we will exceed CO_2eq when the rate of change of emissions is >1% per year, as noted by Lynch et al. (2020). The difference between CO_2eq and CO_2we suggests that GWP may underestimate, or that GWP* may overestimate, the relative strength of CH_4 to CO_2 under increasing annual CH_4 emissions in the near term after a pulse emission, and that GWP may overestimate them in the long term, as was also found in studies using idealized (e.g., hypothetical, as opposed to historical) CH_4 emissions (Lynch et al., 2020).

Because CH_4 is a flow pollutant, under constant annual CH_4 emissions the rate of generation and removal of CH_4 are approximately equal over the atmospheric lifetime of CH_4 and there is no net accumulation of CH_4. To demonstrate that GWP* can capture this short-lived behavior, Lynch et al. (2020) simulated a step increase to a sustained emission of CH_4, and found that over the first 20 years, CO_2we given by GWP* exceeded emissions given by conventional GWP. After the first 20 years, however, the rate of change of CH_4 emissions is 0, and the only CH_4 emissions are those represented by the "stock" or s term (Cain et al., 2019). At the same time, GWP-derived emissions remain above zero with constant annual CH_4 emissions which represents the behavior of a stock gas like CO_2. Similarly, in our BAU scenario under approximately constant annual CH_4 emissions, CO_2eq remain constant, while CO_2we fall almost to zero except for the contribution of the stock term (Figure 3).

4.3. Linking cumulative CO_2we with temperature change

Under decreasing annual CH_4 emissions rates, more CH_4 will have been removed from the atmosphere than is produced to replace it, and negative annual CO_2we emissions suggest negative warming relative to the reference year in our study. Annual CO_2eq under decreasing annual CH_4 emissions, however, were never negative in our study or in that of Lynch et al. (2020).

In the present study, cumulative (annual emissions summed over time) CO_2we dynamics over time match those of warming, which also decrease under decreasing annual CH_4 emissions. Lynch et al. (2020) found that under declining CH_4 emissions, CO_2we were negative, and the temperature effect forced by these declining CH_4 emissions was less positive, like turning down a thermostat (note that any positive CH_4 emissions are still very strong warmers of the climate). In contrast, under declining annual CH_4 emissions, CO_2eq continued to accumulate, and GWP did not indicate the correct direction of temperature change. Thus, warming profiles confirm that GWP*-based cumulative CO_2-warming equivalent emissions are able to represent the warming effects of CH_4 on the climate. Zhang et al. (2018) found that under declining SLCP emissions in the RCP 42.6 and 4.5 emission scenarios, effective radiative forcing from SLCP was negative. Cain et al. (2019) and Lynch et al. (2020) concluded that GWP* captures the fundamentally different behavior of short- vs. long-lived climate pollutants, especially under declining CH_4 emissions, and therefore provides a reliable metric to directly link greenhouse gas emissions to warming.

Due to their linear relationship, cumulative CO_2 emissions can be linked to global temperature change with a coefficient known as the Transient Climate Response to Cumulative Carbon Emissions (TCRE). Cumulative CO_2we should result in global temperature change when multiplied by this constant, and this constant is approximately the slope of a line when cumulative emissions and warming are plotted against each other. Given the similar dynamics of warming and cumulative emissions over time, cumulative emissions could simply be multiplied by a constant, which was ~0.001 mK/Tg CO_2, or 1 K/Tt CO_2, to give temperature change. GWP-based estimates, however, could not be linked to temperature changed simply using a coefficient because cumulative CO_2eq had different dynamics over time than warming. Like Cain et al. (2019) we also found that GWP*-based estimates plotted against temperature change resulted in a straight line, while GWP-based estimates did not. We found this line had an approximate slope of 1 K/Tt CO_2. The approximate change in temperature per unit cumulative CO_2 emissions that we found, 1 K/Tt CO_2, exceeds the IPCC likely range, possibly due to a large increase in annual CH_4 emissions in the 1950s leading to a larger GWP of CH_4 in this time period (Reisinger et al., 2011). The largest discrepancy between the dynamics of GWP*-based estimates and warming is during the period from 1950 to 1980, where a "bulge" occurred, possibly due to this increased GWP of CH_4.

Using Equation 6 and setting CO_2we to zero, Cain et al. (2019), found the rate of CH_4 emission that is equivalent to zero CO_2we and thus to approximately stable temperatures over the time period Δt. With $r = 0.75$, $s = 0.25$, and $H = 100$ years, as used in the present study (following Cain et al., 2019), 0.3% is the rate of decline of CH_4 emissions ($\Delta E/\Delta t$) under which CH_4-induced warming is stable. Under the "Manure 40 plus 3NOP" reduction scenario in the present study, the annual rate of decline of total CH_4 emissions from 2017 to 2030 is about 1.15%, while under "Manure 40 plus BAU EF," the rate of decline of total CH_4 emissions is about 0.92%. Thus, under future SB 1383-mandated emissions reductions, California dairy CH_4 emissions will warm the climate less than they do without these reductions, even under scenarios that limit manure management CH_4 emissions reductions only. The rate of decline of historical CH_4 emissions from the peak in 2008 to 2017, was 3.26%, a decline which we suggest has been driven by declining California dairy herd size driven by increasing per capita milk production, as well as by the CDFA DDRDP after its introduction in 2015, with a minor contribution from AMMP. Thus, under their current and predicted rates of reduction, California dairy CH_4 emissions will be below the level at which stable warming effect will be actuated by these emissions and will reduce warming vs. 20 years ago. This behavior contrasts with CO_2, whose atmospheric concentrations and radiative forcing increase even under decreased emissions rates.

4.4. Contribution of SLCP to California emissions and applicability of GWP* to emissions inventories

Mitigating SLCP emissions from dairy production centers on reducing CH_4 emissions from dairy manure management and reducing CH_4 from enteric fermentation. California has the largest dairy herd in the United States and thus the highest total (enteric fermentation plus manure management) dairy CH_4 emissions. California milk production feed efficiency is relatively high, making enteric fermentation emissions per unit California milk product relatively low (Naranjo et al., 2020). However, CH_4 emissions from cows in California are relatively higher on a per-dairy basis than those in the rest of the United States herd because flush water lagoon systems are the predominate manure management system in California dairies (CARB, 2022b), and anaerobic lagoons emit the most CH_4 per head of all common manure management practices (Owen and Silver, 2015). In 2017, agricultural manure management was California's second largest source of CH_4. Thus, preventing anaerobic conditions during manure management or capturing transforming CH_4 that is produced in anaerobic conditions represent major opportunities to reduce CH_4 from manure management (Montes et al., 2013). The CDFA Dairy Digester Research and Development Program (DDRDP) provides grants to finance the installation of dairy digesters, which capture CH_4 and convert it into fuel (CDFA, 2022b). CDFA's Alternative Manure Management Program (AMMP) provides grants to finance implementation of non-digester manure management practices in order to manage less manure anaerobically, such as solid separation or conversion from flushing to scraping or pasture-based management (CDFA, 2022a). Thus, CDFA's manure management CH_4 emissions reductions programs encompass both major targets for reductions. We have shown in this study that CDFA's programs, especially DDRDP, have successfully mitigated CH_4 emissions and have contributed to the decreasing CH_4 emissions rate in California since 2008.

In 2017, enteric fermentation was California's largest source of methane. Mitigation strategies for enteric fermentation center on use of feed additives such as rumen archaea inhibitors, ionophore antibiotics, or electron acceptors like nitrates (Hristov et al., 2014), and improved feed digestibility, which is unlikely to yield significant benefits in intensive production systems like California that already have relatively high feed efficiency (Herrero et al., 2016). 3NOP inhibits the methane-forming step in the rumen and is a promising feed additive, but production of 3NOP also emits GHG, decreasing net potential reductions (Feng and Kebreab, 2020). In this study, we evaluated reductions scenarios that included enteric fermentation CH_4 reduction, using maximum net potential 3NOP reductions. For our manure management reduction scenarios, we used 40% reduction of 2013 levels as mandated by SB 1383 without evaluating the feasibility of these reductions and assumed 40% represented net reductions. For this reason, enteric fermentation's relatively smaller impact on emissions reductions in our scenarios is not necessarily representative of its true impact relative to manure management mitigation programs. Indeed, over the past 50 years in California, reductions in CH_4 from enteric fermentation have been about five times greater than reductions in CH_4 from manure management (Naranjo et al., 2020). However, because California SB 1383 does not require any specific enteric fermentation reductions, we used potential net 3NOP reductions, while we assumed that 40% manure management methane reductions were feasible because they are mandated by SB 1383. Nonetheless, our study demonstrated that GWP* can accurately represent the warming effects of CO_2eq under potential enteric fermentation CH_4 reductions and thus can serve as an important tool of evaluating on-farm CH_4 mitigation strategies in the future.

We used 2017 enteric fermentation emission factors to calculate emissions from dairy cows from 2017 to 2029 under the "business-as-usual" scenario, assuming that enteric fermentation emissions factors would be stable from 2017 to 2029. However, the true dynamics of future enteric fermentation emissions factors may be more complex. Enteric CH_4 emissions factors for California dairy cattle remained constant from 2012 to 2020 (CARB, 2022a). In contrast, U.S.-wide emissions factors increased by 8.7% from 2010 to 2020 (EPA, 2022). The relative stability of California dairy enteric CH_4 emissions factors may reflect interplay between increasing milk production and improvements in feed efficiency. Increased per capita milk production could associated with greater feed intake and thus increasing enteric CH_4 emissions factors, as both CARB and EPA develop enteric CH_4 emissions factors CH_4 conversion rate, which is the fraction of gross energy (GE) in feed converted to CH_4, and GE intake increases with increasing net energy for lactation (NE_L), which itself increases with increasing milk production (IPCC, 2006; CARB, 2022a; EPA, 2022). However, a life cycle analysis comparing California dairy environmental footprints in 1964 and 2014 found that in 1964, the feed conversion rate was 1.93 kg feed per kg energy-corrected milk (ECM), while in 2014, the feed conversion ratio was 0.79–0.81 kg of feed/kg of ECM, suggesting cattle today utilize feed more efficiently than those 50 years ago. In 1964, each cow emitted 0.98 kg of CO_2 equivalents of enteric methane per kg ECM compared with 0.43–0.45 kg of CO_2 equivalents of enteric methane per kg ECM in 2014 (Naranjo et al., 2020). Average ECM production in 1964 was 15.73 kg/day, while it was 39.8 kg/day in 2014, making enteric methane emissions factors 15.4 kg CO_2 equivalents per day in 1964 and 17.11–17.9 kg CO_2 equivalents per day in 2014.

Previous authors have predicted future inventories of livestock methane emissions assuming constant or even decreasing CH_4 emissions intensities (emissions per unit product, where product is kg of protein in this case) (Chang et al., 2021). Chang et al. projected livestock methane emissions out to 2050 using different pathways of assumed emission intensity changes. These authors used two pathways with contrasting assumptions about production efficiency changes: constant emission intensity and improving efficiency (i.e., decreasing emission intensity). The "constant intensity" pathway assumed that no changes in methane emission intensities would take place in the future. The "improving efficiency" pathway was based on decreasing trends in emission intensity during the past two decades due to increasing production efficiency. Based on this finding, they constructed a "improving efficiency" pathway, assuming continuing decreases in emission intensity. Under this pathway, emissions intensities in countries showing decreasing emission intensity during the past two decades followed this decreasing trend into the future, while a constant emission intensity was applied for countries that experienced no change or an increasing emission intensity in the past two decades. Thus, other studies in the field have found it reasonable to assume constant emissions intensity of livestock products into the future. The assumption that increasing production efficiency will lead to constant or decreasing emissions intensities is not necessarily the same as the assumption that increasing production efficiency will lead to constant emissions *factors*, because increasing production could still lead to increasing total (e.g., not on a per-product basis) emissions. However, enteric CH_4 emissions factors for California dairy cattle given by CARB remained constant from 2012 to 2020. Over this time, California milk production was as follows: 23,457 lbs. per head in 2012; 23,178 lbs. per head in 2013; 23,786 lbs. per head in 2014; 23,028 in 2015; 22,968 in 2016; 22,755 in 2017; 23,301 in 2018; 23,533 in 2019; and 23,990 in 2020 (USDA National Agricultural Statistics Service, 2022). Annual change in milk production, averaged over these 8 years, is 0.26%. Thus, if milk production was approximately constant, and milk emissions intensity was approximately constant or decreasing, then enteric CH_4 per cow (e.g., enteric CH_4 emissions factor) could remain approximately constant.

Because CH_4 emissions factors are estimated based on dietary and production parameters, if regionally typical diets and production remain approximately the same over time, emissions factors will remain the same from year to year. CARB likely has assumed that the diets of California dairy cattle have remained approximately constant, given that the emissions factors they have calculated remain constant from 2012 to 2020. Thus, several lines of evidence underscore that it is a reasonable assumption that enteric fermentation factors will remain approximately constant to 2029 in the BAU scenario. However, this trend does not necessarily apply to other states and production situations, and enteric fermentation emissions factors may be more variable than assumed in our study. In the BAU scenario, this assumption led to approximately constant annual CH_4 emissions, and thus declining GWP* emissions over time. Had enteric CH_4 emissions factors continued to rise over time, the dynamics of the scenario would be similar to the historic (1950–2017) scenario, in which enteric CH_4 emissions factors and annual CH_4 emissions did increase over time. The purpose of our "BAU" scenario was to investigate GWP* dynamics relative to GWP dynamics given approximately constant annual CH_4 emissions. The "BAU" scenario utilized projected dairy cattle population data to estimate future populations under typical policy and macroeconomic conditions and projected a 0.32% decrease in population from 2018 to 2029. This small decrease in population over time, along with the constant enteric fermentation and manure management CH_4 emissions factors used, gives approximately constant annual CH_4 emissions and provides a scenario to investigate the difference in dynamics between GWP- and GWP*-based estimates under *constant* background CH_4 emissions, unlike the historical (increasing background emissions) or reductions (decreasing background emissions) scenarios. Thus, while further investigation on trends in enteric fermentation and manure management emissions factors and future dairy cattle populations is needed, the assumption of constant California CH_4 emissions factors from 2017 to 2029 is in line with CARB emissions factors and sufficient for our study's purposes.

The goal of California's annual GHG emission inventory is to establish historical emission trends and track sectoral progress in achieving statewide reductions goals. The 2021 edition of the inventory and previous iterations provide emissions estimates in CO_2eq using GWP_{100} values from IPCC AR4, consistent with current international and national GHG inventory practices (CARB, 2022a). In addition, SB 1383 mandates reductions in annual emissions rates, not warming effects, of dairy manure CH_4 by 2030. Thus, because goals are centered on emissions reductions, not warming impacts, GWP may still be an appropriate metric for these purposes. However, attribution of the warming impacts of the economic sectors whose emissions are quantified in emissions inventories requires a metric that can capture the dynamics of cumulative SLCP emissions over time, such as GWP*. GWP* and GWP could coexist given the different policy goals of economic sectors or state or local governments, as recommended by the IPCC AR6 Working Party I report.

4.5. Limitations of GWP*

Notwithstanding GWP*'s improved representation of CH_4's flow gas-nature, any single-number metric may result in oversimplification of complex climate dynamics and underestimation of the warming response to SLCP emissions (Collins et al., 2020). Some arbitrary decisions still underlie GWP*, such as the time horizon H, or the designation of a certain climate pollutant as "short-lived" and thus the employment of GWP*, which depends on the time scale being considered (Lynch et al., 2020). While the calculation of GWP* is subject to some arbitrary decisions, the concept of CO_2eq is not necessarily physically accurate. Climate responses to CO_2 and CH_4 are both temperature- and scenario-dependent, so different emissions scenarios with identical CO_2eq can have vastly different impacts on global temperature. For this reason, no single scaling factor can truly convert between CO_2 and CH_4 emissions across all scenarios (Fuglestvedt et al., 2000).

Previous authors have suggested that because it is based on past emissions, GWP* unfairly and unethically penalizes developing countries when applied at sub-global levels (Rogelj and Schleussner, 2019). Rogelj and Schleussner argue that due to GWP*'s "grandfathering" effect, countries with high historic SLCP emissions are rewarded because reductions from these emissions lead to declining cumulative CO_2we, while countries with historically low SLCP emissions (i.e., typically developing countries) are penalized for increasing emissions which may result from socioeconomic development. While not stated in this critique, presumably similar limitations apply to emissions from specific economic sectors. In their response, Cain et al. (2021) note that this "unintentional unfairness" would result from any warming-equivalent-based metric that differentiates the behavior of stock and flow pollutants, such as combined global temperature change potential (CGTP) (Collins et al., 2020). Furthermore, because IPCC AR6 does not recommend any given emission metric, metric appropriateness depends on given policy goals. Cain et al. (2021) argue that in policy contexts with long-term temperature goals as the Paris Agreement, GWP* is useful because it demonstrates that the relationship between a country's CH_4 emissions and temperature change scales with current CH_4 emissions plus a contribution from past CH_4 emissions, which conventional GWP cannot. They argue that quantifying this relationship is not itself necessarily unfair or unequitable, given that quantification of historical contributions of a country's SLCP to warming using GWP* and taking these contributions into burden-sharing policy are separate, and the latter are determined by policy-makers, although using a metric that reflects the impact of all gases on temperature change would facilitate such policy discussions (Cain et al., 2021).

In spite of potential limitations of the CO_2 equivalence concept and GWP*, CO_2-equivalence-based climate metrics remain a prevalent policy tool (UNFCCC, 2020). GWP* provides an accessible and temperature goal-relevant adjustment of current CO_2-equivalence methodology that does not require any additional information from what is already typically reported. Other metrics that have been proposed as alternatives to GWP, such as Global Temperature Change Potential (GTP), combined GWP, or CGTP, require additional inputs that are themselves dependent on uncertainties in the climate system and future emissions scenarios (Shine et al., 2007; Collins et al., 2020). GWP* has been shown to underestimate the contribution of CH_4 to temperature change by up to 20% compared to CGTP, which employs a more explicit calculation of the effect of CH_4 emissions rate change relative to a pulse emission of CO_2 (Collins et al., 2020). However, Collins et al. (2020) also note that the more complex emissions metrics CGWP or GTP are structurally similar to GWP* and provide only changes in precise values, not conceptual foundation or development, whereas using the conventional GWP is unable to represent the correct sign of warming from decreasing SLCP emissions, as we have shown. While Wigley (1998) argues that unlike the GWP framework, emissions equivalence should be based on radiative-forcing based Forcing Equivalence Index (FEI), other authors consider both GWP and GWP* reasonable approximations to FEI (Enting and Clisby, 2021).

5. Conclusions

We have used California dairy production as a case study for the application of the novel GHG metric GWP*, following its recent development and publication. While recent publications have shown the applicability of GWP* to global emissions datasets spanning all SLCP emissions sectors, we have applied GWP* to a California dairy CH_4 emissions inventory and discussed the applicability of GWP* to local and single-sector inventories, which some authors argue is limited. GWP* provides a direct relationship between cumulative emissions and their warming effects, which conventional GWP does not. This relationship exists because GWP* represents methane's short-lived nature, by which it does not accumulate in the atmosphere under declining emissions, unlike CO_2. We found that conventional GWP underrepresents the warming impacts of dairy CH_4 emissions in CA under increasing emissions rates, and overrepresents their warming impacts under declining emissions rates. GWP* represents that under declining emissions rates, cumulative California dairy CH_4 decrease and warming forced by these emissions also decreases, although any CH_4 that continues to be emitted is still a strong climate forcer. In contrast, under declining annual CH_4 emissions, GWP-based CO_2-equivalent emissions (CO_2eq) continued to accumulate, so GWP did not indicate the correct direction of temperature change. While IPCC AR6 makes clear that metric choice depends on policy goals, given its ability to unambiguously link warming impacts to SLCP emissions, GWP* may provide a more accurate tool for quantifying SLCP emissions into policy contexts that specifically aim to limit global warming, such as the Paris Agreement.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

EP designed the research approach, compiled data, wrote the R code to analyze the results, analyzed the results, and prepared the manuscript. SL helped design the research approach and provided data and support in carrying out the research. FM proposed the research question and supervised the work. All authors reviewed drafts of the manuscript, provided feedback, and approved the final version.

Funding

Financial support to EP was provided by the Students Training in Advanced Research (STAR) Program at the UC Davis School of Veterinary Medicine through the Ritchie Hill endowment funds, SAVMA AWESC Environmental Awareness Grant, and NIH Grant T32GM136559.

Acknowledgments

We gratefully acknowledge Joe Proudman for his helpful feedback. We acknowledge researchers at FAPRI and AMAP for providing information about the methodology used in FAPRI/AMAP projections.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1072805/full#supplementary-material

References

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., et al. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 458, 1163–1166. doi: 10.1038/nature08019

Allen, M. R., Shine, K. P., Fuglestvedt, J. S., Millar, R. J., Cain, M., Frame, D. J., et al. (2018). A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *NPJ Clim. Atmos. Sci.* 1, 1–8. doi: 10.1038/s41612-018-0026-8

Blayney, D., and Normile, M. A. (2004). *Economic Effects of U.S. Dairy Policy and Alternative Approaches to Milk Pricing: Report to Congress (Administrative Publication Number 076)*. Washington, DC: USDA. Available online at: http://ageconsearch.umn.edu (accessed August 16, 2022).

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., et al. (2013). Bounding the role of black carbon in the climate system: a scientific assessment. *J. Geophys. Res. Atmos.* 118, 5380–5552. doi: 10.1002/jgrd.50171

Cain, M., Lynch, J., Allen, M. R., Fuglestvedt, J. S., Frame, D. J., and Macey, A. H. (2019). Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *NPJ Clim. Atmos. Sci.* 2, 4. doi: 10.1038/s41612-019-0086-4

Cain, M., Shine, K., Frame, D., Lynch, J., Macey, A., Pierrehumbert, R., et al. (2021). Comment on "Unintentional unfairness when applying new greenhouse gas emissions metrics at country level". *Environ. Res. Lett.* 16, 68001. doi: 10.1088/1748-9326/ac02eb

Capper, J. L., Cady, R. A., and Bauman, D. E. (2009). The environmental impact of dairy production: 1944 compared with 2007. *J. Anim. Sci.* 87, 2160–2167. doi: 10.2527/jas.2009-1781

CARB (2022a). *3A1ai—Livestock—Enteric Fermentation—Cattle—Dairy Cows Year 2019, Documentation of California's Greenhouse Gas Inventory*. Sacramento, CA: CARB. Available online at: https://ww2.arb.ca.gov/sites/default/files/ghg-inventory-doc/newdoc/docs3/3a1ai_entericfermentation_livestockpopulation_dairycows_ch4_2019.htm (accessed August 12, 2022).

CARB (2022b). *3A2ai—Livestock—Manure Management—Cattle—Dairy Cows Year 2019, Documentation of California's Greenhouse Gas Inventory*. Sacramento, CA: CARB. Available online at: https://ww2.arb.ca.gov/applications/california-ghg-inventory-documentation (accessed August 12, 2022).

CARB (2022c). *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target*. Sacramento, CA: CARB. Available online at: https://ww2.arb.ca.gov/resources/documents/dairy-livestock-sb1383-analysis (accessed August 12, 2022).

CDFA (2000). *California Agricultural Resource Directory 2000*. Baltimore: CDFA.

CDFA (2007). *California Agricultural Resource Directory 2006*. Baltimore: CDFA.

CDFA (2022a). *Alternative Manure Management Program, Office of Environmental Farming and Innovation*. Baltimore: CDFA. Available online at: https://www.cdfa.ca.gov/oefi/ammp/ (accessed August 12, 2022).

CDFA (2022b). *Dairy Digester Research and Development Program, Office of Environmental Farming and Innovation*. Baltimore: CDFA. Available online at: https://www.cdfa.ca.gov/oefi/ddrdp/ (accessed August 12, 2022).

Chang, J., Peng, S., Yin, Y., Ciais, P., Havlik, P., and Herrero, M. (2021). The key role of production efficiency changes in livestock methane emission mitigation. *AGU Adv.* 2, 391. doi: 10.1029/2021AV000391

Collins, W. J., Frame, D. J., Fuglestvedt, J. S., and Shine, K. P. (2020). Stable climate metrics for emissions of short and long-lived species—combining steps and pulses. *Environ. Res. Lett.* 15, 024018. doi: 10.1088/1748-9326/ab6039

Cui, T., Ding, Z., and Fu, X. (2017). Effects of straw and biochar addition on soil nitrogen, carbon, and super rice yield in cold waterlogged paddy soils of North China. *J. Integ. Agric.* 16, 1064–1074. doi: 10.1016/S2095-3119(16)61578-2

den Elzen, M. G. J., and Lucas, P. L. (2005). The FAIR model: a tool to analyse environmental and costs implications of regimes of future commitments. *Environ. Model. Assess.* 10, 115–134. doi: 10.1007/s10666-005-4647-z

Dijkstra, J., Bannink, A., France, J., Kebreab, E., and van Gastelen, S. (2018). Short communication: antimethanogenic effects of 3-nitrooxypropanol depend on supplementation dose, dietary fiber content, and cattle type. *J. Dairy Sci.* 101, 9041–9047. doi: 10.3168/jds.2018-14456

Duin, E. C., Wagner, T., Shima, S., Prakash, D., Cronin, B., Yáñez-Ruiz, D. R., Duval, S., Rümbeli, R., Stemmler, R. T., Thauer, R. K., and Kindermann, M. (2016). Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol. *Proc. Natl. Acad. Sci.* 113, 6172–6177. doi: 10.1073/pnas.1600298113

Enting, I., and Clisby, N. (2021). Technical note: On comparing greenhouse gas emission metrics. *Atmos. Chem. Phys.* 21, 4699–4708. doi: 10.5194/acp-21-4699-2021

EPA (2013a). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2011 U.S. Environmental Protection Agency. Annex 3.10: Methodology for Estimating CH4 Emissions from Enteric Fermentation*. Washington, DC: EPA. Available online at: https://www.epa.gov/sites/default/files/2015-12/documents/us-ghg-inventory-2013-annexes.pdf (accessed August 10, 2022).

EPA (2013b). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2011 U.S. Environmental Protection Agency. Annex 3.11: Methodology for Estimating* CH_4 *and* N_2O *Emissions from Manure Management*. Washington, DC: EPA. Available online at: https://www.epa.gov/sites/default/files/2015-12/documents/us-ghg-inventory-2013-annexes.pdf (accessed November 6, 2022).

EPA (2022). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020 Annex 3.10*. Washington, DC: EPA. Available online at: https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-annex-3-additional-source-or-sink-categories-part-a.pdf

Fabiosa, J., Beghin, J., De Cara, S., Elobeid, A., Fang, C., Isik, M., et al. (2005). The doha round of the world trade organization and agricultural markets liberalization: impacts on developing economies. *Rev. Agric. Econ.* 27, 317–335. doi: 10.1111/j.1467-9353.2005.00252.x

FAPRI and AMAP (2020a). *Baseline Review 2020: U.S. Livestock and Dairy Tables, University of Missouri*. Washington, DC: FAPRI and AMAP. Available online at: https://www.fapri.missouri.edu/baseline-review-2020/ (accessed August 11, 2022).

FAPRI and AMAP (2020b). *US Agricultural Market Outlook: Agricultural Markets and Policy Trade Friction Baseline and a Phase 1 Scenario (FAPRI-MU Report #01-20)*. Missouri: University of Missouri. Available online at: https://www.fapri.missouri.edu/publication/2020-u-s-agricultural-market-outlook/ (accessed August 12, 2022).

Feng, X., and Kebreab, E. (2020). Net reductions in greenhouse gas emissions from feed additive use in California dairy cattle. *PLoS ONE* 15, e0234289. doi: 10.1371/journal.pone.0234289

Fuglestvedt, J. S., Berntsen, T. K., Godal, O., Sausen, R., Shine, K. P., and Skodvin, T. (2003). Metrics of climate change: assessing radiative forcing and emission indices. *Clim. Change* 58, 267–331. doi: 10.1023/A:1023905326842

Fuglestvedt, J. S., Berntsen, T. K., Godal, O., and Skodvin, T. (2000). Climate implications of GWP-based reductions in greenhouse gas emissions. *Geophys. Res. Lett.* 27, 409–412. doi: 10.1029/1999GL010939

Gulev, S. K., Thorne, P. W., Ahn, J., Dentener, F. J., Domingues, C. M., Gerland, S., et al. (2021). "Changing state of the climate system," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Cambridge, New York, NY: Cambridge University Press).

Herrero, M., Henderson, B., Havlík, P., Thornton, P. K., Conant, R. T., Smith, P., et al. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nat. Clim. Change* 6, 452–461. doi: 10.1038/nclimate2925

Hörtenhuber, S. J., Seiringer, M., Theurl, M. C., Größbacher, V., Piringer, G., Kral, I., et al. (2022). Implementing an appropriate metric for the assessment of greenhouse gas emissions from livestock production: a national case study. *Animal* 16, 100638. doi: 10.1016/j.animal.2022.100638

Hristov, A. N., Oh, J., Firkins, J. L., Dijkstra, J., Kebreab, E., Waghorn, G., et al. (2014). SPECIAL TOPICS: mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options 1. *J. Anim. Sci.* 91, 5045–5069. doi: 10.2527/jas.2013-6583

IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. Geneva: IPCC

IPCC (2021). "Summary for policymakers," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* eds V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, et al. (Cambridge: Cambridge University Press).

Johnson, S. R., Meyers, W. H., Devadoss, S., Westhoff, P., Helmar, M. D., Skold, K. D., et al. (1993). "Policy Scenarios with the FAPRI Modeling System (No. 606)," in *Agricultural Sector Models for the United States*. Ames: Iowa State University Press.

Kai, F. M., Tyler, S. C., Randerson, J. T., and Blake, D. R. (2011). Reduced methane growth rate explained by decreased Northern Hemisphere microbial sources. *Nature* 476, 194–197. doi: 10.1038/nature10259

Lamarque, J. F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., et al. (2010). Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmos. Chem. Phys.* 10, 7017–7039. doi: 10.5194/acp-10-7017-2010

Lara (2016). *Senate Bill No. 1383 Chapter 395*. New York, NY: California State Senate. Available online at: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB1383 (accessed August 10, 2022).

Lynch, J., Cain, M., Pierrehumbert, R., and Allen, M. (2020). Demonstrating GWP: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short-A and long-lived climate pollutants. *Environ. Res. Lett.* 15, 44023. doi: 10.1088/1748-9326/ab6d7e

Matthews, H. D., Gillett, N. P., Stott, P. A., and Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature* 459, 829–832. doi: 10.1038/nature08047

Millar, R. J., Nicholls, Z. R., Friedlingstein, P., and Allen, M. R. (2017). A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmos. Chem. Phys.* 17, 7213–7228. doi: 10.5194/acp-17-7213-2017

Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A. N., Oh, J., et al. (2013). SPECIAL TOPICS: Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. *J. Anim. Sci.* 91, 5070–5094. doi: 10.2527/jas.2013-6584

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., et al. (2013). "Anthropogenic and natural radiative forcing," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia,

V. Bex, and P. M. Midgley (Cambridge; New York, NY: Cambridge University Press), 659–740. Available online at: https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

Naranjo, A., Johnson, A., Rossow, H., and Kebreab, E. (2020). Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years. *J. Dairy Sci.* 103, 3760–3773. doi: 10.3168/jds.2019-16576

Nisbet, E. G., Manning, M. R., Dlugokencky, E. J., Fisher, R. E., and Lowry, D. (2016). Rising atmospheric methane: 2007–2014 growth and isotopic shift. *Glob. Biogeochem. Cycles* 30, 1356–1370. doi: 10.1002/2016GB005406

Ocko, I. B., Sun, T., Shindell, D., Oppenheimer, M., Hristov, A. N., Pacala, S. W., et al. (2021). Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. *Environ. Res. Lett.* 16, 054042. doi: 10.1088/1748-9326/abf9c8

Owen, J. J., and Silver, W. L. (2015). Greenhouse gas emissions from dairy manure management: a review of field-based studies. *Glob. Change Biol.* 21, 550–565. doi: 10.1111/gcb.12687

Persson, U. M., Johansson, D. J., Cederberg, C., Hedenus, F., and Bryngelsson, D. (2015). Climate metrics and the carbon footprint of livestock products: Where's the beef? *Environ. Res. Lett.* 10, 5. doi: 10.1088/1748-9326/10/3/034005

Pierrehumbert, R. T. (2014). Short-lived climate pollution. *Ann. Rev. Earth Planet. Sci.* 42, 341–379. doi: 10.1146/annurev-earth-060313-054843

R Core Team (2020). *R: A Language and Environment for Statistical Computing*. New York, NY: R Foundation for Statistical Computing. Available online at: https://www.r-project.org (accessed August 10, 2022).

Reisinger, A., Havlik, P., Riahi, K., Van Vliet, O., Obersteiner, M., and Herrero, M. (2013). Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. *Clim. Change* 117, 677–690. doi: 10.1007/s10584-012-0593-3

Reisinger, A., Meinshausen, M., and Manning, M. (2011). Future changes in global warming potentials under representative concentration pathways. *Environ. Res. Lett.* 6, 024020. doi: 10.1088/1748-9326/6/2/024020

Ridoutt, B. (2021a). Climate neutral livestock production: a radiative forcing-based climate footprint approach. *J. Clean. Prod.* 291, 125260. doi: 10.1016/j.jclepro.2020.125260

Ridoutt, B. (2021b). Short communication: climate impact of Australian livestock production assessed using the GWP* climate metric. *Livestock Sci.* 246, 104459. doi: 10.1016/j.livsci.2021.104459

Ridoutt, B., Lehnert, S. A., Denman, S., Charmley, E., Kinley, R., and Dominik, S. (2022). Potential GHG emission benefits of Asparagopsis taxiformis feed supplement in Australian beef cattle feedlots. *J. Clean. Prod.* 337, 130499. doi: 10.1016/j.jclepro.2022.130499

Rogelj, J., and Schleussner, C.-F. (2019). Unintentional unfairness when applying new greenhouse gas emissions metrics at country level. *Environ. Res. Lett.* 14, 114039. doi: 10.1088/1748-9326/ab4928

Schaefer, H., Fletcher, S. E. M., Veidt, C., Lassey, K. R., Brailsford, G. W., Bromley, T. M., et al. (2016). A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by 13CH4. *Science* 352, 80–84. doi: 10.1126/science.aad2705

Schwietzke, S., Sherwood, O. A., Bruhwiler, L. M., Miller, J. B., Etiope, G., Dlugokencky, E. J., Michel, S. E., Arling, V. A., Vaughn, B. H., White, J. W., and Tans, P. P. (2016). Upward revision of global fossil fuel methane emissions based on isotope database. *Nature* 538, 88–91. doi: 10.1038/nature19797

Shine, K. P., Berntsen, T. K., Fuglestvedt, J. S., Skeie, R. B., and Stuber, N. (2007). Comparing the climate effect of emissions of short- and long-lived climate agents. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 365, 1903–1914. doi: 10.1098/rsta.2007.2050

Smith, C. J., Forster, P. M., Allen, M., Leach, N., Millar, R. J., Passerello, G. A., et al. (2018). FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* 11, 2273–2297. doi: 10.5194/gmd-11-2273-2018

Smith, M. A., Cain, M., and Allen, M. R. (2021). Further improvement of warming-equivalent emissions calculation. *NPJ Clim. Atmos. Sci.* 4, 19. doi: 10.1038/s41612-021-00169-8

Smith, S. J., and Wigley, T. M. L. (2006). Multi-gas forcing stabilization with Minicam. *Energy J.* 65, SI2006(01). doi: 10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-19

Solomon, S., Qin, D., Manning, M., Averyt, K., and Marquis, M. (2007). *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

UNFCCC (2020). *Common Metrics*. Bonn: UNFCCC. Available online at: https://unfccc.int/process-and-meetings/transparency-and-reporting/methods-for-climate-change-transparency/common-metrics (accessed August 10, 2022).

USDA National Agricultural Statistics Service (2019). *Quick Stats*. Washington, DC: USDA National Agricultural Statistics Service. Available online at: https://quickstats.nass.usda.gov (accessed August 10, 2022).

USDA National Agricultural Statistics Service (2022). *Quick Stats*. Washington, DC: USDA National Agricultural Statistics Service. Available online at: https://quickstats.nass.usda.gov (accessed December 12, 2022).

Westhoff, P., and Brown, D. S. (1999). The U.S. dairy sector without price supports. *Can. J. Agric. Econ. Revue Canadienne D Agroeconomie* 47, 19–27. doi: 10.1111/j.1744-7976.1999.tb00235.x

Wigley, T. M. L. (1998). The Kyoto protocol: CO_2 CH_4 and climate implications. *Geophys. Res. Lett.* 25, 2285–2288. doi: 10.1029/98GL01855

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., et al. (2009). Implications of limiting CO_2 concentrations for land use and energy. *Science* 324, 1183–1186. doi: 10.1126/science.1168475

Zhang, H., Xie, B., and Wang, Z. (2018). Effective radiative forcing and climate response to short-lived climate pollutants under different scenarios. *Earth's Fut.* 6, 857–866. doi: 10.1029/2018EF000832

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 09 March 2023
DOI 10.3389/fsufs.2023.1111361

Check for updates

Assessing the diet quality, environmental impact, and monetary costs of the dietary transition in China (1997–2011): Impact of urbanization

Zhiyao Chang[1,2,3†], Hongyi Cai[1,2,3†], Elise F. Talsma[2], Shenggen Fan[3,4], Yuanying Ni[1], Xin Wen[1*], Pieter van't Veer[2] and Sander Biesbroek[2]

[1]College of Food Science and Nutritional Engineering, China Agricultural University, Beijing, China, [2]Division of Human Nutrition and Health, Wageningen University & Research, Wageningen, Netherlands, [3]Academy of Global Food Economics and Policy, China Agricultural University, Beijing, China, [4]College of Economics and Management, China Agricultural University, Beijing, China

Background: Increased urbanization has been linked to transitions in dietary patterns. However, evidence on the impacts of urbanization on diet quality, and environmental impact, and diet cost is limited. The aim of this study was to investigate the time trends of these three dietary sustainability in China over the period 1997–2011 and to examine their associations with urbanization.

Methods: Food consumption of 8,330 participants (18–64y) of the China Health and Nutrition Survey cohort (1997, 2000, 2004, 2006, 2009, and 2011) were examined and diet quality was assessed using the Chinese Healthy Eating Index 2016 (CHEI2016). Dietary related environmental impacts on Greenhouse Gas Emissions (GHGE), Total Water Use (TWU), and Land Use (LU) were estimated using the Chinese Food Life Cycle Assessment Database. Monetary cost of diet was calculated using the community market prices of food items. Multilevel mixed-effects models were used to estimate associations between the time trend of dietary sustainability indicators and degree of urbanization.

Results: From 1997 to 2011, the CHEI2016 score increased by 10.6%, GHGE by 23.8%, LU by 29.1%, and the inflation-corrected cost of diet by 80%. Urbanization was positively associated with these time trends, which remained after adjustment for sociodemographic and lifestyle factors (all $P < 0{\cdot}05$).

Conclusion: The rapid urbanization in China over the past two decades has been followed by an improvement in the overall dietary quality, but this has been accompanied by an increase in the environmental impacts and higher cost of the diet, especially in communities with lower urbanization index.

KEYWORDS

diet trends, sustainability, urbanization, China, diet quality, diet-related environmental impacts, cost of diet, multilevel model

OPEN ACCESS

EDITED BY
Aida Turrini,
Independent Researcher, Rome, Italy

REVIEWED BY
Rena I. Kosti,
University of Thessaly, Greece
Lorenza Mistura,
Council for Agricultural and Economics Research (CREA), Italy

*CORRESPONDENCE
Xin Wen
✉ xin.wen@cau.edu.cn

[†]These authors have contributed equally to this work

SPECIALTY SECTION
This article was submitted to Nutrition and Sustainable Diets, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 29 November 2022
ACCEPTED 17 February 2023
PUBLISHED 09 March 2023

CITATION
Chang Z, Cai H, Talsma EF, Fan S, Ni Y, Wen X, Veer Pv and Biesbroek S (2023) Assessing the diet quality, environmental impact, and monetary costs of the dietary transition in China (1997–2011): Impact of urbanization. *Front. Sustain. Food Syst.* 7:1111361. doi: 10.3389/fsufs.2023.1111361

Introduction

The current global food system is facing the challenges of a growing population and increasing environmental, health, and economic problems (FAO, 2022). These trends are associated with urbanization processes trend and diet shifts toward high consumption levels of animal products, cooking oils, salt, and sugar, which is increasing the prevalence of overweight, obesity, and hypertension (Afshin et al., 2019). In the context of population growth, these dietary transitions are having an increasingly negative impact on climate change, water resources, land availability, and ecosystems (Johnston et al., 2014; Tilman and Clark, 2014). Additionally, 3 billion people are currently unable to afford a healthy diet (Herforth et al., 2020).

China has the highest growth rate of urbanization in the world over the past four decades (18% in 1978 to 65% in 2021) (Yang, 2013), the increasing urbanization indicates a growing modernized living environment with improved food environment, health care, communication, infrastructure, etc. (Fong et al., 2019). Dietary patterns are shifting from a grain and vegetable-based diet to a diet high in red meat and processed foods (Du et al., 2004), consequently affecting human health and the environment (Xiong et al., 2022). Moreover, the increase in overweight in rural areas of China was 64.5% higher compared to urban areas in 2000–2020 (Huang et al., 2021). Although the diet-related greenhouse gas emissions (GHGE) of rural residents in China are lower than those of urban residents, this gap is narrowing (He et al., 2018).

A sustainable diet, which considers the role of dietary patterns for sustainable development, posts a positive effect on public health (reduction of diet-related chronic diseases, etc.), environmental sustainability (reduction of greenhouse gas emissions, water and land use), and economic sustainability (increased affordability of diets) (FAO and WHO, 2019). To alleviate the resource constraints and food insecurity caused by rapid urbanization, it is necessary to redefine dietary patterns from a health, environmental, and economic perspective (Clark et al., 2019). Most studies focus their analysis and interpretation on a single dimension of sustainability, e.g. the nutritional dimension, or several environmental indicators (mainly GHGE). Few studies have focused on these sustainability dimensions simultaneously (Macdiarmid, 2013; Willett et al., 2019; Hirvonen et al., 2020). Furthermore, there is limited empirical evidence on changes in urbanization as related to dietary quality, diet-related environmental impacts and cost of diet in China.

Therefore, this study attempts to answer the questions: What are the trends of diet quality, diet-related environmental impacts, and cost of diets during the period from 1997 to 2011, and does the changes depend on the level of urbanization?

Data and methodology

Study population and dietary data

The China Health and Nutrition Survey (CHNS) is an ongoing longitudinal and international cohort project. The CHNS collect individual-level data of the health, nutrition, and the community-level as well as household-level data of family planning policies and programs implemented by national and local governments (China Health and Nutrition Survey, 2014). The current research is based on the data of wave 1997, 2000, 2004, 2006, 2009, and 2011 and is drawn from the 9 provinces or autonomous cities/districts, including Guangxi, Guizhou, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Liaoning, and Shandong. The dietary assessment is based on a combination of data collected at the individual level with 3 consecutive 24-h dietary recalls and a food inventory taken at the household level over the same 3-day period. To collect individual dietary data, every household member (aged 12 years or older) was asked to report all food consumed over the previous 24 h for each of the 3 days.

Diets of adults aged 18–64 years were evaluated. Exclusion of the records in the dataset was based on the following criteria: children (<18y, n = 2,469, 14.6% of sample) and elderly (>65y, n = 2,768, 17.7% of sample), lactating and pregnant women (n = 417, 0.38% of sample), as well as those with a Z-score >5 for energy intake (n = 524; 0.42% of sample). The final sample included 8,330 in 1997, 7,453 in 2000, 6,078 in 2004, 5,767 in 2006, 5,230 in 2009, and 4,756 in 2011. All the adult participants have reliable dietary intake and with non-missing values on key demographic and behavioral variables for this analysis.

Chinese Healthy Eating Index 2016

The Chinese Healthy Eating Index 2016 (CHEI2016) was used to assess the quality of the diet as a dietary sustainability indicator of health (Yuan et al., 2017). The index used standard portion of foods as the unit of dietary measurement, and standard portion is defined as a food that contains the same amount of energy and has similar carbohydrate, fat and protein content within the same food group (Supplementary Table 1). The CHEI2016 consists of 12 food components in terms of adequacy (cereals, whole grains and mixed beans, tubers, total vegetables (exclude dark vegetables), dark vegetables, fruits, dairy, soybeans, fish and seafood, poultry, eggs, and seeds and nuts) and 5 food components in terms of limitation (red meat, edible oils, sodium, added sugar and alcohol). Most food components were rated on a scale from 0 to 5, except for fruit, cooking oil and salt, which were rated on a scale from 0 to 10, with higher scores indicating a higher quality diet. The minimum and maximum cut-off values for each food component were based on the recommendations of the Chinese Dietary Guidelines 2016, and the scores were distributed linearly between the minimum and maximum cut-off values. The total CHEI2016 score is the sum of the 17 food component scores, ranging from 0 to 100, with 100 representing the highest dietary quality.

Environmental impact of diets

The environmental impact of foods in the CHNS samples was evaluated by linking them to the Chinese Food Life Cycle Assessment Database (CFLCAD). Details of the CFLCAD can be found elsewhere (Cai et al., 2022). In the database, Greenhouse Gas Emissions (GHGE) for 80 food items, Total Water Use (TWU) for 93 food items, and Land Use (LU) for 50 food items were collected, as the dietary sustainability indicators of diet-related environmental impacts. When no LCA data of a certain food were available, data from food groups with similar nutritional composition or cultivation condition were used as proxies. To harmonize the system boundaries, the database covers the 6 life cycle stages of all foods in the CHNS: production, processing, storage, packaging, transportation, food preparation stages, as well as the loss rates in the food chain.

Costs of diets

The cost of diets was evaluated as the dietary sustainability indicator from the economic perspective of the consumers. The CHNS conducted a detailed community survey consisting of food market information such as infrastructure, services, and organization, as well as the prices of foods at the community level (Guo et al., 1999, 2000). The food groups collected in CHNS consist of 13 food categories: cereals and tubers, legumes, vegetables, fruit and nuts, meat, poultry, dairy, eggs, aquatic products, beverages and fast food, liquor and alcohol, fats and oils, and condiment (vinegar, soy sauce). For all food categories, we use the least free market prices by default, and substitute with lowest retail prices wherever free market prices are missing. Using a free market price for each specific food commodity from CHNS, total daily monetary costs were calculated by multiplying the cost per g (RMB/g) of each food item by the reported daily quantity consumed through the 3 day 24 h dietary recall survey. Inflation adjustment is accomplished by multiplying the cost of diet by the Consumer Price Index of 2011.

Urbanization index

The CHNS used the urbanization index as a multidimensional measure to determine the level of urbanization of the respective community. This index consists of 12 community indicators, namely population density, economic activity, traditional markets, modern markets, transportation and health infrastructure, sanitation, communication, social services, diversity and housing. The 12 components were calculated based on the amount of infrastructure present in the community, the percentage of households in the community, and a maximum score of 10 for each indicator (with a range of 0–10, Supplementary Table 2). The detailed construction procedure, scale scoring algorithms, cut-off values and the dataset of the index are available in the supplementary material of the work of Jones-Smith and Popkin (2010).

Covariates

Sociodemographic and behavior data obtained using the CHNS questionnaire included age (in years), sex (male or female), height, weight, work-related physical activity, educational level, and dietary knowledge. The Body Mass Index was calculated using self-reported height and weight. The categories of work-related physical activity were light (e.g., sedentary job, office work, watch repairers, counter salesperson, lab technician), moderate (e.g., driver, electrician) and heavy (e.g., farmer, athlete, dancer, steel worker, lumber worker, mason). CHNS classified education level as follows: no school (0 year), primary school (1–6 years), junior middle school (1–3 years), senior middle school (1–3 years), middle technical or vocational school (1–2 years), college (3–4 years in college/university), and graduate school (over 4 years in college/university). Educational level was then divided into three categories of low (no school; primary school; junior middle school); medium (senior middle school; middle technical or vocational school), and high educational level (college; graduate school). Proportion of animal-based foods (%) in the diet was determined by dividing the animal-based food consumption (including: meat, poultry, dairy, egg and aquatic products) (g) by the total food consumption (g).

Statistical analysis

The mean and standard deviation (SD) of the dietary sustainability indicators (CHEI2016, environmental impacts, and cost of diet) of all participants were described. Energy intake was highly correlated with diet quality and diet-related environmental impacts and cost of diet, thus dietary sustainable indicators were recalculated per 2,000 kcal/d.

The crude secular trends of variables were statistically evaluated by the Jonckheere–Terpstra test in the cohort study (Vock and Balakrishnan, 2010). The participants were categorized into quartiles of urbanicity index and tested for differences in diet-related GHGE, TWU, LU, CHEI2016, and cost of diet across the quartiles of urbanicity index using one-way analysis of variance (ANOVA). The mediation analyses was conducted for urbanization index (predictor variable) and each dietary sustainability indicator (dependent variable), with the proportion of animal-based food consumption (mediator) and demographic characteristics (covariates) using the Sobel-Goodman mediation test.

Likelihood ratio tests were used to compare the fit of nested models (Random intercept models as well as multilevel random slope and intercept regression models) for effect measure modifiers and goodness of fit, and the results showed that the fit of multilevel random slope and intercept regression model was better (Supplementary Table 3). The longitudinal tracking data in CHNS violated the assumptions of data independence and homogeneity of variance because of the nested structure. Therefore, a two-level random slope and intercept regression model with individuals (level 1) nested within community (level 2) was used to estimate the association between sustainable indicators of diet and urbanization index.

The main analysis was replicated in two multilevel analyses: Model 1 included one of the three dietary sustainability indicators and the urbanization index with adjustments for individual-level explanatory variables (age, gender, BMI, education level, activity level, income, and dietary knowledge). In Model 2, the urbanization index was deconstructed into its 12 subcomponents and the individual-level variables were the same as in Model 1. In each model, the intra-class coefficient of correlation (ICC) was calculated as the ratio of between-community variance to total variance of dietary sustainability indicators (Snijders and Bosker,

10.3389/fsufs.2023.1111361

TABLE 1 Cross-sectional univariate descriptive of participants in the CHNS 1997-2011, aged 18–64 years[a].

	1997 (n = 8,330)		2000 (n = 7,453)		2004 (n = 6,078)		2006 (n = 5,767)		2009 (n = 5,230)		2011 (n = 4,756)		p-trend[b]
Gender													
Male	4,131	49.6%	3,641	48.9%	2,948	48.5%	2,767	48.0%	2,531	48.4%	2,265	47.6%	0.016*
Female	4,199	50.4%	3,812	51.1%	3,130	51.5%	3,000	52.0%	2,699	51.6%	2,491	52.4%	0.017*
Age (years)	39.4	12.5	43.5	11.9	48.4	11.4	50.5	11.2	53.3	11.3	55.4	11.1	<0.001***
Resident place													
Urban area	2,755	33.1%	2,400	32.2%	1,862	30.6%	1,733	29.1%	1,491	28.5%	1,288	27.1%	0.272
Rural area	5,575	66.9%	5,053	67.8%	4,216	69.4%	4,216	70.9%	3,739	71.5%	3,468	72.9%	0.278
BMI (kg/m^2)	22.3	3.1	22.9	3.2	23.2	3.3	23.3	3.6	23.5	3.4	23.9	4.9	<0.001***
Educational level													
Below primary school	6,632	79.6%	5,833	78.3%	4,784	78.7%	4,488	75.4%	4,285	81.9%	3,901	82.0%	0.712
Secondary school	1,492	17.9%	1,351	18.1%	1,101	18.1%	1,055	17.7%	789	15.1%	666	14.0%	0.851
Above high school	206	2.5%	269	3.6%	193	3.2%	224	3.8%	156	3.0%	189	4.0%	0.033*
Activity level													
Low	3,175	38.1%	2,764	37.1%	2,493	41.0%	2,401	40.4%	2,424	46.3%	2,288	48.1%	0.003**
Medium	1,337	16.1%	1,090	14.6%	978	16.1%	872	14.7%	690	13.2%	686	14.4%	0.587
High	3,818	45.8%	3,599	48.3%	2,607	42.9%	2,494	41.9%	2,116	40.5%	1,782	37.5%	0.029*
Dietary knowledge													
No	Not measured		Not measured		5,547	93.8%	5132	89.9%	4,600	88.7%	3,829	81.2%	0.042*
Yes	Not measured		Not measured		369	6.2%	576	10.1%	588	11.3%	889	18.8%	0.041*
Income (1,000 RMB/Y, inflated to 2011)	2,520.6	1,387.4–4,159.1	2,984.1	1,504.6–5,018.5	3,565.6	1,835.1–6,666.7	3,999.1	1,920.1–7,716.6	7,000.1	3,605.1–12,766.6	9,025.1	4,651.6–16,400.1	<0.001***
Dietary Energy (kcal/d)	2,368	714	2,297	650	2,239	669	2,211	675	2,167	678	2,050	972	<0.001***
Proportion of animal-based foods (%)	11.3	0.1	12.7	0.1	12.2	0.1	12.9	0.1	13.1	0.1	12.1	0.1	<0.001***
Urbanization index	52.6	18.1	58.1	18.1	60.3	20.1	61.9	19.8	64.5	18.6	64.5	18.2	<0.001***

[a]Continuous variables were expressed by means and SD (except income variable was expressed by median and IQR). Categorical variables were expressed by number and percentage.

[b]p-value for the trend was determined by the Jonckheere–Terpstra test. For categorical variables, this study examined trends in percentages by years. Jonckheere-Terpstra test is a rank-based nonparametric test that is used to determine if there is a statistically significant trend between an ordinal independent variable and a continuous or ordinal dependent variable. The * symbol indicates the *P*-value for significance <0.001. The ** symbol indicates the *P*-value for significance <0.01 and *** symbol indicates the P-value for significance < 0.05.

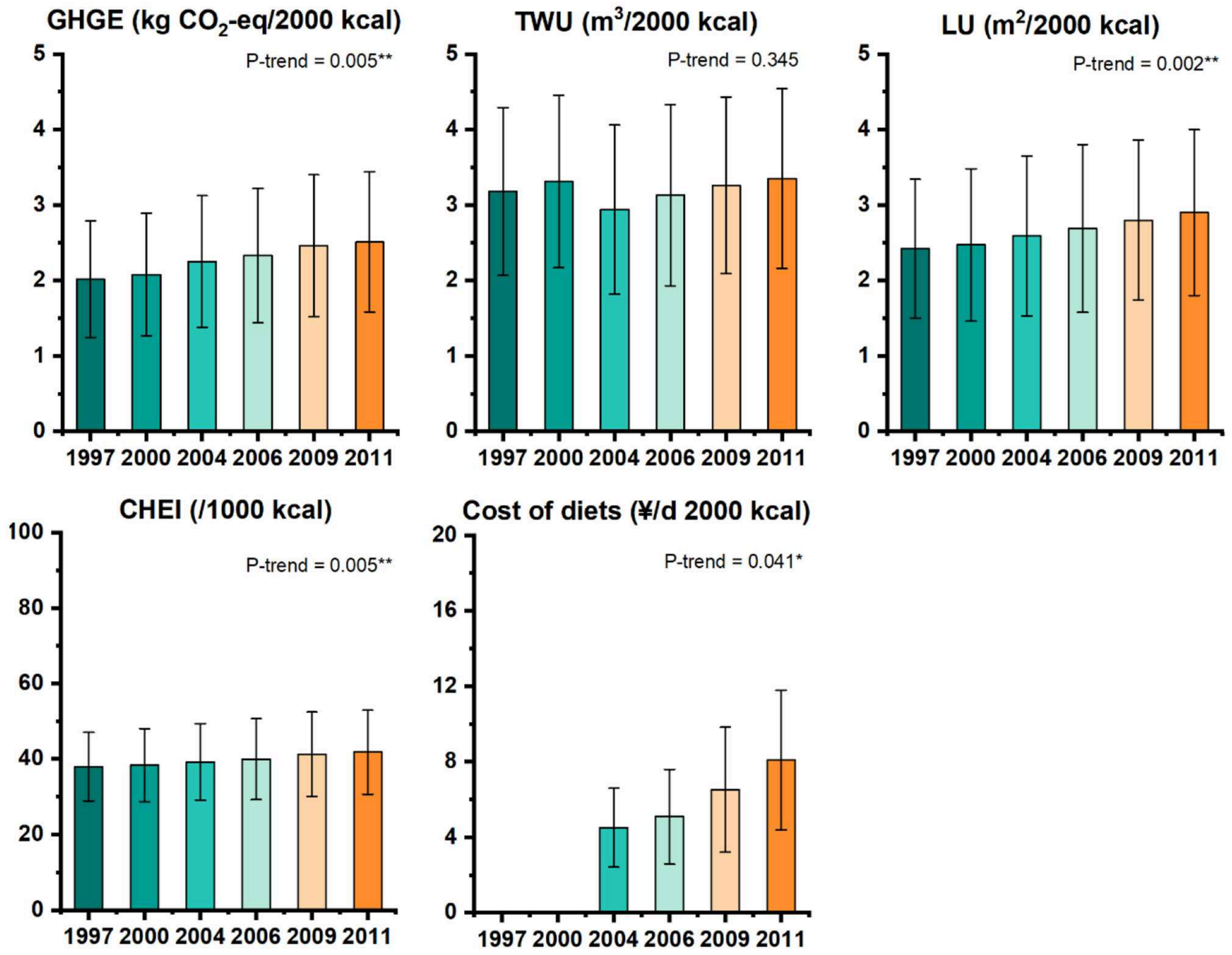


FIGURE 1
Mean and standard deviation of the diet-related GHGE, TWU, LU, CHEI2016, and cost of diet in the CHNS 1997–2011[a]. [a]Food price data is available from 2004 onwards. p-trend = 0.005** for GHGE, P-trend = 0.345 for TWU, P-trend = 0.002** for LU, p-trend = 0.005** for CHEI2016, p-trend = 0.041* for cost of diet. The p-trend was based on Jonckheere–Terpstra test.

2011). The closer ICC to 1, the larger the proportion of the variance that can be attributed to community level characteristics rather than individual characteristics (Raudenbush and Bryk, 2002). To assess the goodness of fit of these models Akaike's Information Criterion (AIC) was used (Akaike, 1974). The interaction between urbanization index and survey year was tested to evaluate whether the time trend of the dietary sustainability indicators differs by the degree of urbanization.

All data collation and statistical analyses were performed with Stata/se 13.1 (Stata Corp). All reported p-values were two-tailed, with a P-value < 0.05 considered statistically significant.

Results

The cohort study consisted of 8,330 people at baseline and reduced over the years to 4,756 in the final round (Table 1). From 1997 to 2011, activity levels and energy intake of participants decreased while BMI, per capita income, and educational level increased. The mean urbanization index increased as well from 52.6 (±18.1 SD, 1997) to 64.5 (±18.2 SD, 2011).

Between 1997–2011, a significant increasing time trend was observed for the CHEI2016 ($p = 0.005$), dietary GHGE ($p = 0.005$), LU ($P = 0.002$), and dietary cost ($p = 0.041$), while the TWU ($p = 0.345$) fluctuated during the same period (Figure 1 and Supplementary Table 4). The CHEI2016 score was 37.9 in 1997 and increased to 41.9 in 2011 (+ 10.6%). Dietary GHGE progressively increased by 23.8% (0.6 kg CO_2-eq/2000 kcal/d per person) and LU increased by 29.1% (0.7 m^2/2,000 kcal/d per person) respectively. Dietary TWU was 3.2 in 1997 and 3.4 m^3/2,000 kcal in 2011. Similarly, the inflation-corrected diet cost rose by 80.0% from 4.5 RMB/d/2,000 kcal in 2004 to 8.1 RMB/d/2,000 kcal in 2011.

A higher degree of urbanization was associated with higher diet-related CHEI2016, GHGE, TWU, LU, and cost of diet from 1997 to 2011 (Figure 2). Also during the past two decades, the increase of indicators was larger in the lowest as compared to highest quartiles of urbanization. CHEI2016 in the lowest vs. highest urbanization quartile increased by 18.1% compared to 7.4%, diet-related GHGE increased by 86.9% compared to 17.8%, TWU increased by 38.4% compared to −0.9%, LU increased by 57.8 vs. 13.1%, and cost of diet increased by 124.4% compared to 64.7% from 2004 to 2011.

Dietary sustainability indicators were positively associated with the urbanization index (*P*-for trend <0.05) in Model 1 after adjustment for individual-level covariates and survey year (Table 2). An increase of 0.241 kg CO_2-eq/2,000 kcal (GHGE), 0.289 m^3/2,000 kcal (TWU), 0.198 m^2/2,000 kcal (LU), 2.843 per 1000 kcal (CHEI2016), and 1.108 RMB/d/2,000 kcal (cost of diet) for highest vs. lowest quartile of urbanization index (Q4 vs. Q1). The ICC coefficient for Model 1 all exceeded 0.7, indicating there was substantial inter-community heterogeneity in dietary sustainable indicators. The proportion of animal-based food in diet consumption showed a positive correlation with CHEI2016, diet-related environmental impacts (GHGE, TWU, and LU), and cost of diet, respectively ($p<0.001$). The interaction between urbanization index and survey year was significant ($p<0.001$). Model 2 further performed multilevel analyses of the 12 sub scores of the urbanization index: "Communication", Economic activity, Housing infrastructure, and Sanitation were significantly positively associated with each of the environmental impact indicators, while Education was negatively associated. Health infrastructure was positively associated with GHGE and TWU but had no association with LU. In terms of the health indicator, Population density, Housing infrastructure, and Education showed a positive association with CHEI2016. Moreover, cost of diet was positively associated with Housing infrastructure, Traditional markets, and Sanitation. The proportion of animal-based foods in the diet might be an intermediary factor between urbanization and dietary sustainability outcomes as Mediation analysis showed that animal-based foods could explain 24.5% (CHEI2016), 9.2% (GHGE), 13.8% (TWU), 11.3% (LU) and 38.1% (cost of diet) of the overall association between urbanization and these sustainability outcomes (Sobel-Goodman mediation test, all $p<0.001$; see Supplementary Table 5).

Discussion

This study showed that while diet quality increased 10.6% as indicated by the CHEI2016, also the dietary GHGE increased 23.8%, LU increased 29.1% during the period 1997 to 2011, and dietary costs increased by 80% between 2004 to 2011. These time trends were more pronounced in the lowest quartile of urbanization as compared to the highest: CHEI2016 in the lowest vs. highest quartile of urbanization increased by 18.1% compared to 7.4%, diet-related GHGE increased by 86.9% compared to 17.8%, TWU increased by 38.4% compared to −0.9%, LU increased by 57.8% compared to 13.1%, and cost of diet increased by 124.4% compared to 64.7%. Mediation analysis indicates that these associations are mediated by the consumption of animal-based foods. Between-community differences explained over 70% of this population's total variability in dietary sustainable indicators, suggesting that community-level variables are essential factors that are driving these trends.

As a low- and middle-income country (LMIC) China is in the midst of rapid urbanization and therefore provides a suitable context to study the role of urbanization on the sustainability of diets. This study showed that all indicators were highest in highly urbanized areas. In line with this, an almost tenfold increase of animal sourced food consumption in China was reported, correlating with a rapidly growing degree of urbanization and modernization from 1961 to 2000 (FAO., 2005). Previous studies compared sustainable diets in rural and urban areas in LMICs (Auestad and Fulgoni, 2015; Downs et al., 2017; Batis et al., 2021; Castellanos-Gutiérrez et al., 2021), and the results of these studies suggest that the better dietary quality in more urbanized areas goes along with increased environmental impacts and higher cost of diet (United Nations Department of Economics Social Affairs, 2012). Therefore, for higher urbanized areas, it is necessary to promote a dietary pattern that is healthy, low in diet-related environmental impacts, and at an affordable cost to ensure the health of the planet and the population. The multilevel analysis of this study suggested that the sustainability indicators in low urbanized areas are catching up with higher urbanized areas. An important challenge lies in accompanying the continued growth of urbanization and modernization in less urbanized areas, which means diets in these areas would follow the changes toward more animal-based foods as higher urbanized areas have already been undergoing. Moreover, as the proportion of animal-based food was a intermediator of this association, the results suggested that urbanization may have shaped the context for a diet shift toward a high intake of red meats, poultry, and eggs, with associated diet costs and subsequent environmental impacts. These results underpin the close interrelationship between economic development, agricultural supply, and demand for more expensive animal foods. Therefore, to reduce the adverse environmental impacts of this economic development, not only increase the public awareness about the health, environmental impacts, and cost of diets need to be increased that can promote more sustainable dietary choices, but also require interrelated changes in supply and demand. Consequently, promoting more sustainable dietary choices for consumers.

Using population size and density alone as a measure of urbanization is biased (Ng et al., 2009). Indeed, the concept of urbanization in this study tends to represent the degree of modernization beyond the population size and density. Modernization has an impact on the dietary transition in terms of transportation, health service, and social services (Zhou et al., 2015). The associations observed in the analysis suggest that the impact of urbanization on sustainable indicators might vary depending on various aspects of urbanization. When this study decomposed the overall urbanization index into its sub-scores (while controlling for the other sub-scores), population density was associated to the CHEI2016 only and not to the environmental indicators or diet costs. The components of Communication, Economic activity, Housing infrastructure, and Sanitation were significantly associated with dietary environmental impacts. A previous study concluded that the higher the per capita income of a household and the more urbanized the area, the more likely the population is to consume more sugar, fat, and highly processed and packaged foods (Colozza and Avendano, 2019). The increasing complexity of food processing has increased the environmental footprint of food. These conclusions were in line with present study which demonstrated that the component of Economic

TABLE 2 Coefficients from two-level mixed effect models for dietary environmental impacts, CHEI2016, and cost of diet among adults aged 18–64 years, CHNS 1997–2011[a].

		GHG emissions (kg CO_2-eq/2,000 kcal)		Total water use (m^3/2,000 kcal)		Land use (m^2/2,000 kcal)		CHEI2016 (/1,000 kcal)		Cost of diet (RMB/d/2,000 kcal)	
	Effects	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Fixed effects											
Level-1 (Individual level variables)											
Survey year (ref. =1997)[b]											
	2000	0.086***	0.105***	0.167***	0.185***	0.075***	0.083***	−0.656***	−0.724***	Not measured	
	2004	0.231***	0.215***	−0.256***	−0.274***	0.152***	0.119***	0.563**	0.391	Not measured	
	2006	0.304***	0.267***	−0.065**	−0.108***	0.245***	0.183***	1.225***	0.999***	0.537***	0.505***
	2009	0.417***	0.362***	0.044	−0.033	0.337***	0.251***	2.364***	2.177***	1.921***	1.861***
	2011	0.501***	0.435***	0.169***	0.088*	0.491***	0.388***	3.112***	2.823***	3.423***	3.338***
Proportion of animal-based foods (per 10%)		0.548***	0.549***	0.546***	0.548***	0.538***	0.541***	2.472***	2.481***	0.228***	0.228***
Age (per 10 years)		−0.041***	−0.040***	−0.051***	−0.061***	−0.041***	−0.051***	−0.441***	−0.441***	−0.031	−0.031
Gender (ref. = female)		0.021**	0.021**	0.075***	0.071***	0.044***	0.044***	−2.081***	−2.081***	0.057	0.056
BMI (kg/m^2)		0.004***	0.004***	0.005**	0.002	0.006**	0.005***	0.031*	−0.031*	0.011**	0.011**
Income (1,000 RMB/Y, inflated to 2011)		0.004***	0.004***	0.005***	0.005***	0.005***	0.004***	0.063***	0.062***	0.003	0.003
Education level (ref. = Below primary school)											
	Secondary school	0.075***	0.076***	0.087**	0.079***	0.105***	0.106***	0.891***	0.872***	0.146**	0.148***
	Above high school	0.107***	0.115***	0.107**	0.129**	0.118***	0.121***	0.716*	0.667*	0.183*	0.187*
Activity level (ref. = Low)											
	Medium	−0.024	−0.026*	−0.041*	−0.058**	−0.044*	−0.044*	0.701	0.072	−0.081	−0.077
	High	−0.165***	−0.163***	−0.193***	−0.186***	−0.195***	−0.191***	−0.327*	−0.306*	−0.167***	−0.161***
Level-2 (Community variables)											
Urbanization index (per Q4 vs. Q1)[c]		0.241 **		0.289*		0.198***		2.843**		1.108*	
Interaction: Urbanization index*Survey year		−0.001***		−0.001***		−0.001*		−0.004*		−0.002*	
Urbanization components (per SD)											
General sub scores											
	Population density		−0.001		−0.041		−0.001		0.745***		0.008
	Education		−0.077***		−0.061*		−0.052*		0.571**		−0.109
	Economic activity		0.044***		0.051***		0.044***		0.197		0.025

(Continued)

TABLE 2 (Continued)

	Effects	GHG emissions (kg CO_2-eq/2,000 kcal)		Total water use (m^3/2,000 kcal)		Land use (m^2/2,000 kcal)		CHEI2016 (/1,000 kcal)		Cost of diet (RMB/d/2,000 kcal)	
		Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
	Transportation infrastructure		0.007		0.026*		0.005		0.103		0.002
	Social services		−0.002		−0.008		−0.002		0.002		0.067
	Education and income diversity		0.014		0.038		0.023		−0.019		0.083
Sub scores with relevance to health and food domain											
	Housing infrastructure		0.049**		0.072***		0.063***		0.367*		0.144**
	Sanitation		0.039**		0.042*		0.057***		0.189		0.311***
	Communication		0.021**		0.054***		0.027***		0.064		0.001
	Health infrastructure		0.017*		0.041***		0.007		0.002		0.015
	Traditional markets		−0.004		−0.014		0.014		−0.094		0.177***
	Modern markets		−0.003		−0.012		−0.015		0.539		0.015
Random effects											
Variance of slope		0.001	0.001	0.001	0.001	0.001	0.001	0.073	0.071	0.018	0.019
Variance of intercept		1.953	1.918	4.159	3.9476	2.553	2.467	236.804	233.753	66.101	71.961
Variance of residual		0.536	0.535	1.099	1.097	0.971	0.969	75.271	75.198	4.396	4.382
ICC[d]		0.784	0.781	0.791	0.784	0.724	0.718	0.758	0.748	0.937	0.942
AIC		77,660	77,619	102,345	102,547	97,891	97,868	247,796	247,764	89,944	89,916

[a]Model 1: included individual and community variables; Model 2: added urbanization components instead of urbanization index in community level from Model 1.
[b]For the cost of diet, the survey year is referenced to 2004.
[c]Unit was based on the mean of quintile 4 minus quintile 1.
[d]The inter-class correlation coefficient (ICC) is a ratio of between-community variance to total variance in dietary sustainability indicators.
The * symbol indicates the P-value for significance <0.001. The ** symbol indicates the P-value for significance <0.01 and *** symbol indicates the P-value for significance < 0.05.

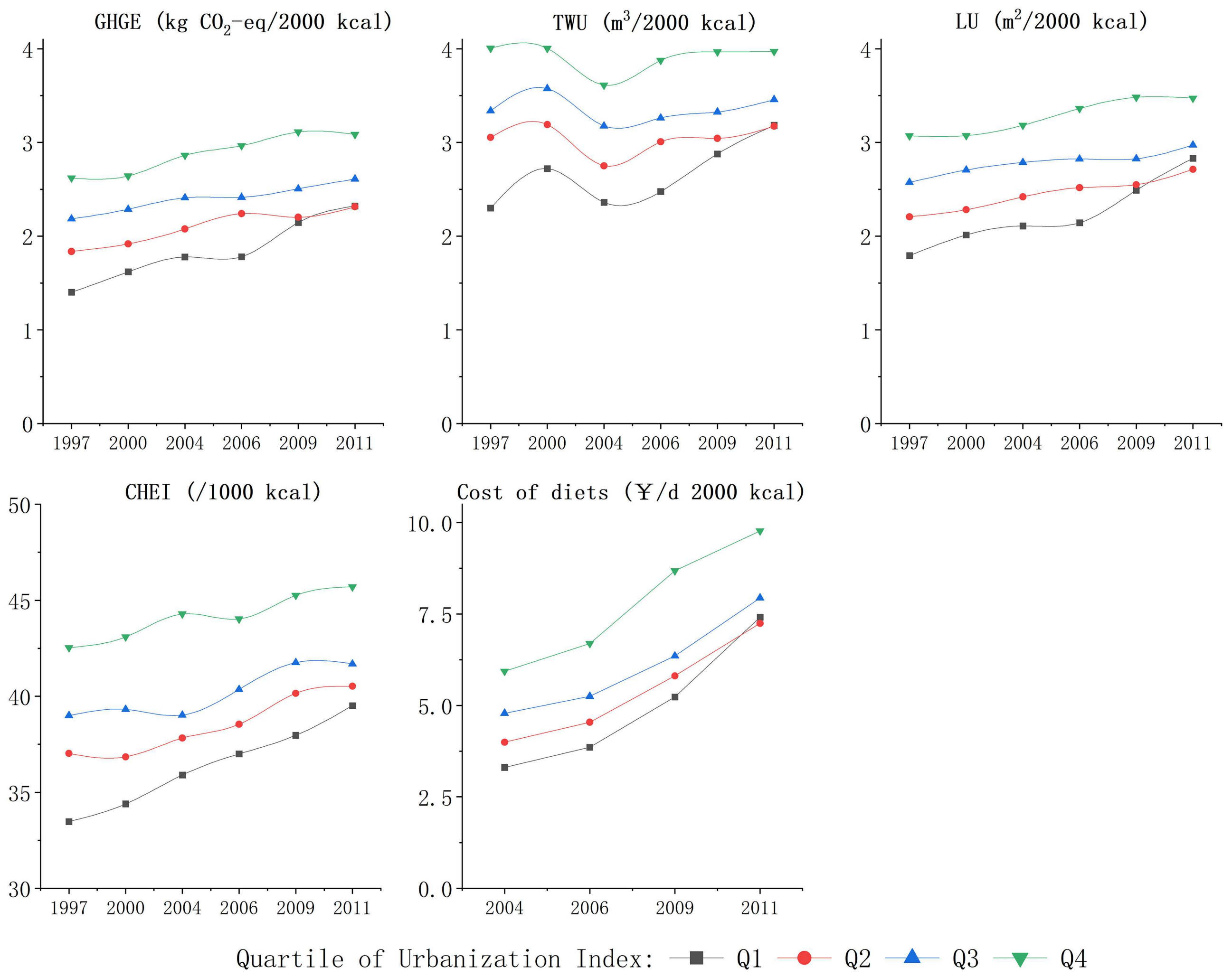


FIGURE 2
Diet-related GHGE, TWU, LU, CHEI2016, and cost of diet by quartiles of the urbanization index in the CHNS 1997-2011.

activity was positively associated with the diet-related GHGE, TWU, and LU, respectively. Furthermore, due to the increased accessibility of communication devices, residents are able to receive advertisements for dairy products, snacks, convenience foods, and fast food outlets on television, the internet, and mobile phones (Huang et al., 2015), thus potentially increasing the frequency of consumption of these foods. This is similar to the results in Model 2, GHGE, TWU, and LU was increased with the growth of the component of communication. The components of Health infrastructure, Housing infrastructure, Traditional markets and Sanitation are positively associated with the cost of diet. Traditional markets can be found in almost all Chinese cities and villages. Animal foods such as meat, dairy products and fish can be accessed directly by the consumers (Zhai et al., 2014). This change in the community environment was associated with a high-fat, high-energy dietary pattern, thus increasing the costs of diets.

Considerable heterogeneity was observed in the association between individual-level variables (such as education and income) and dietary sustainability indicators of Chinese consumers in present study and similar result from the previous study (Su et al., 2020), suggesting that trends in dietary sustainability indicators are not fully explained by community-level variables. Diet-related GHGE, TWU, LU, CHEI2016, and cost of diet showed a strong association with educational levels, respectively. Previous studies have shown that higher educational levels directly influence consumers' concerns about nutrition adequacy, which resulted in improved quality of the diets (Hotz and Gibson, 2005). In addition, education level also influenced consumers' choice of the proportion of animal- and plant-based food, indirectly driving changes in the environmental impacts of food consumption and dietary costs (Aggarwal et al., 2011; Van Bussel et al., 2020). Moreover, as income levels rise, consumers tended to improve the quality of diets. A previous study concluded that the higher the income level of a household, the more likely it is to consume more refined and highly processed and packaged foods (Reynolds et al., 2019). However, the increasing complexity of food processing has also increased the environmental impacts of food.

This current research has several strengths. First, this study benefited from a large sample size and a 15-year follow-up period. Only the individuals with 3-day 24-h recall data were included in this prospective study, which minimizes bias and provides stronger evidence for causality (Kandola et al., 2020). Secondly, this research uses a multilevel mixed effects model to distinguish between community and individual impacts on dietary sustainability indicators. Thirdly, for each community surveyed, the contextual variable urbanization in this study consists of 12 different dimensions of infrastructure, economic, and demographic items. This greatly improves the ability to distinguish the impact of urbanization on the commonly used urban-rural dichotomy (Jones-Smith and Popkin, 2010). This dichotomy not only assumes homogeneity within the "urban" and "rural" categories, but it also ignores change over time. Moreover, the environmental impacts in this study were based on the Chinese Food LCA Database, without using impact estimates from High-Income Countries that would lead to an overestimation of those impacts.

However, some limitations should be mentioned. Given that China has undergone significant changes in recent years in terms of urbanization and dietary transition, however, this study covered only the survey period 1997–2011. Secondly, regional heterogeneity of urbanization can lead to differences in food consumption and its associated sustainability indicators that deserve future attention. This heterogeneity highlights the need for region-specific dietary adjustment strategies. A deeper understanding of the complex associated mechanisms will be of great value for future research.

Conclusions

The present study demonstrated that the rapid urbanization in China over the past two decades has been accompanied by an improvement in overall diet quality, however, also by an increase in the diet-related environmental impacts and cost of the diet. Of special concern was the observed trend that people from the lower urbanization levels are rapidly adopting similar diet-transitions as the highest urbanization quartile. Halting and reversing these dietary trends that are increasing health at the expense of environmental impacts and increased dietary cost is a key challenge for policy makers and nutrition researchers.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Available upon reasonable request from the National Institute for Nutrition and Food Safety, China Center for Disease Control and Prevention. Requests to access these datasets should be directed to chns@unc.edu.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Committees from the University of North Carolina at Chapel Hill and the National Institute for Nutrition and Food Safety, China Center for Disease Control and Prevention approved the survey protocols and instruments and the process for obtaining informed consent for the survey. The patients/participants provided their written informed consent to participate in this study.

Author contributions

ET, PV, and SB designed the research. ZC and HC conducted the analyses and wrote the paper. All authors provided feedback on the manuscript and approved of the final version.

Funding

This project was funded by the Agricultural Green Development Ph.D., Program (No. 201913043) of China Agricultural University and Wageningen University and Research.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1111361/full#supplementary-material

References

Afshin, A., Sur, P. J., Fay, K. A., Cornaby, L., Ferrara, G., Salama, J. S., et al. (2019). Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the global burden of disease study 2017. *Lancet* 393, 1958–1972. doi: 10.1016/S0140-6736 (19)30041-8

Aggarwal, A., Monsivais, P., Cook, A. J., and Drewnowski, A. (2011). Does diet cost mediate the relation between socioeconomic position and diet quality? *Eur. J. Clin. Nutr.* 65, 1059–1066. doi: 10.1038/ejcn.2011.72

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Trans. Automat. Contr.* 19, 716–723. doi: 10.1109/TAC.1974.1100705

Auestad, N., and Fulgoni, V. L. (2015). What current literature tells us about sustainable diets: emerging research linking dietary patterns, environmental sustainability, and economics. *Adv. Nutr.* 6, 19–36. doi: 10.3945/an.114.005694

Batis, C., Marrón-Ponce, J. A., Stern, D., Vandevijvere, S., Barquera, S., Rivera, J. A., et al. (2021). Adoption of healthy and sustainable diets in Mexico does not imply higher expenditure on food. *Nat Food.* 2, 792–801. doi: 10.1038/s43016-021-00359-w

Cai, H., Biesbroek, S., Wen, X., Fan, S., Veer, P. v., and Talsma, E. F. (2022) Environmental footprints of Chinese foods and beverages: literature-based construction of a LCA database. *Data Brief* 42, 108244. doi: 10.1016/j.dib.2022.108244

Castellanos-Gutiérrez, A., Sánchez-Pimienta, T. G., Batis, C., Willett, W., and Rivera, J. A. (2021). Toward a healthy and sustainable diet in Mexico: where are we and how can we move forward? *Am. J. Clin. Nutr.* 113, 1177–1184. doi: 10.1093/ajcn/nqaa411

China Health and Nutrition Survey. (2014). *China Health and Nutrition Survey (CHNS)*. Available online at: https://www.cpc.unc.edu/projects/china (accessed October 12, 2022).

Clark, M. A., Springmann, M., Hill, J., and Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proc. Nat. Acad. Sci.* 116, 23357–23362. doi: 10.1073/pnas.1906908116

Colozza, D., and Avendano, M. (2019). Urbanisation, dietary change and traditional food practices in Indonesia: a longitudinal analysis. *Soc. Sci. Med.* 233, 103–112. doi: 10.1016/j.socscimed.2019.06.007

Downs, S. M., Payne, A., and Fanzo, J. (2017). The development and application of a sustainable diets framework for policy analysis: a case study of Nepal. *Food Policy* 70, 40–49. doi: 10.1016/j.foodpol.05.005

Du, S., Mroz, T. A., Zhai, F., and Popkin, B. M. (2004). Rapid income growth adversely affects diet quality in China—particularly for the poor! *Soc. Sci. Med.* 59, 1505–1515. doi: 10.1016/j.socscimed.01.021

FAO (2022). *The State of Food Security and Nutrition in the World 2022*. Rome: FAO.

FAO and WHO. *Sustainable Healthy Diets: Guiding Principles*. Rome: FAO and WHO (2019). p. 44.

FAO. (2005). *Globalization of Food Systems in Developing Countries: Impact on Food Security and Nutrition*. Rome: FAO. p. 314.

Fong, T. C. T., Ho, R. T. H., and Yip, P. S. F. (2019). Effects of urbanization on metabolic syndrome via dietary intake and physical activity in Chinese adults: Multilevel mediation analysis with latent centering. *Soc Sci Med.* 234, 112372. doi: 10.1016/j.socscimed.2019.112372

Guo, X., Popkin, B. M., Mroz, T. A., and Zhai, F. (1999). Food price policy can favorably alter macronutrient intake in China. *J. Nutr.* 129, 994–1001.

Guo, X., Mroz, T. A., Popkin, B. M., and Zhai, F. (2000). Structural change in the impact of income on food consumption in China, 1989–1993. *Econ. Dev. Cult. Change.* 48, 737–760. doi: 10.1086/452475

He, P., Baiocchi, G., Hubacek, K., Feng, K., and Yu, Y. (2018). The environmental impacts of rapidly changing diets and their nutritional quality in China. *Nat. Sustain.* 1, 122–127. doi: 10.1038/s41893-018-0035-y

Herforth, A., Bai, Y., Venkat, A., Mahrt, K., Ebel, A., Masters, W. A., et al. (2020). *Cost and Affordability of Healthy Diets Across and Within Countries: Background Paper for the State of Food Security and Nutrition in the World 2020. FAO Agricultural Development Economics Technical Study No. 9*. Rome, Italy: FAO. p. 108.

Hirvonen, K., Bai, Y., Headey, D., and Masters, W. A. (2020). Affordability of the EAT–Lancet reference diet: a global analysis. *Lancet Glob. Health* 8, e59–66. doi: 10.1016/S2214-109X (19)30447-4

Hotz, C., and Gibson, R. S. (2005). Participatory nutrition education and adoption of new feeding practices are associated with improved adequacy of complementary diets among rural Malawian children: a pilot study. *Eur. J. Clin. Nutr.* 59, 226–237.

Huang, C.-., C., Yabiku, S. T., and Kronenfeld, J. J. (2015). The effects of household technology on body mass index among Chinese adults. *Popul. Res. Policy Rev.* 34, 877–899. doi: 10.1007/s11113-015-9371-z

Huang, L., Wang, Z., Wang, H., Zhao, L., Jiang, H., Zhang, B., et al. (2021). Nutrition transition and related health challenges over decades in China. *Eur. J. Clin. Nutr.* 75, 247–252. doi: 10.1038/s41430-020-0674-8

Johnston, J. L., Fanzo, J. C., and Cogill, B. (2014). Understanding sustainable diets: a descriptive analysis of the determinants and processes that influence diets and their impact on health, food security, and environmental sustainability. *Adv. Nutr.* 5, 418–429. doi: 10.3945/an.113.005553

Jones-Smith, J. C., and Popkin, B. M. (2010). Understanding community context and adult health changes in China: development of an urbanicity scale. *Soc. Sci. Med.* 71, 1436–1446. doi: 10.1016/j.socscimed.07.027

Kandola, A. A., Osborn, D. P. J., Stubbs, B., Choi, K. W., and Hayes, J. F. (2020). Individual and combined associations between cardiorespiratory fitness and grip strength with common mental disorders: a prospective cohort study in the UK Biobank. *BMC Med.* 18, 303. doi: 10.1186/s12916-020-01782-9

Macdiarmid, J. I. (2013). Is a healthy diet an environmentally sustainable diet? *Proc. Nutr. Soc.* 72, 13–20. doi: 10.1017/S0029665112002893

Ng, S. W., Norton, E. C., and Popkin, B. M. (2009). Why have physical activity levels declined among Chinese adults? Findings from the 1991–2006 China health and nutrition surveys. *Soc. Sci. Med.* (2009) 68, 1305–1314. doi: 10.1016/j.socscimed.01.035

Raudenbush, S. W., and Bryk, A. S. (2002). *Hierarchical Linear Models: Applications and Data Analysis Methods*. Thousand Oaks, CA: SAGE. p. 520.

Reynolds, C. J., Horgan, G. W., Whybrow, S., and Macdiarmid, J. I. (2019). Healthy and sustainable diets that meet greenhouse gas emission reduction targets and are affordable for different income groups in the UK. *Public Health Nutr.* 22, 1503–1517. doi: 10.1017/S1368980018003774

Snijders, T. A. B., and Bosker, R. J. (2011). *Multilevel Analysis: An Introduction to Basic and Advanced Multilevel Modeling*. Thousand Oaks, CA: SAGE. p. 370.

Su, C., Song, X., Hu, H., Du, W., Wang, H., Zhang, B., et al. (2020). Longitudinal association between urbanicity and total dietary fat intake in adults in urbanizing China from 1991 to 2015: findings from the CHNS. *Nutrients.* 12, 1597. doi: 10.3390/nu12061597

Tilman, D., and Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature.* 515, 518–522. doi: 10.1038/nature13959

United Nations Department of Economics and Social Affairs (2012). *World Urbanization Prospects, the 2011 Revision*. Available online at: https://www.un.org/en/development/desa/publications/world-urbanization-prospects-the-2011-revision.html (accessed October 6, 2022).

Van Bussel, L. M., Van Rossum, C. T., Temme, E. H., Boon, P. E., and Ock,é, M. C. (2020). Educational differences in healthy, environmentally sustainable and safe food consumption among adults in the Netherlands. *Public Health Nutr.* 23, 2057–2067. doi: 10.1017/S1368980019005214

Vock, M., and Balakrishnan, N. (2010). A. Jonckheere–Terpstra-type test for perfect ranking in balanced ranked set sampling. *J. Stat. Plan. Inference.* 141, 624–630. doi: 10.1016/j.jspi.07.005

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet.* 393, 447–492. doi: 10.1016/S0140-6736 (18)31788-4

Xiong, X., Zhang, L., Hao, Y., Zhang, P., Shi, Z., Zhang, T., et al. (2022). How urbanization and ecological conditions affect urban diet-linked GHG emissions: new evidence from China. *Res. Conserv. Recycl.* 176, 105903. doi: 10.1016/j.resconrec.2021.105903

Yang, X. J. (2013). China's rapid urbanization. *Science* 342, 310. doi: 10.1126/science.342.6156.310-a

Yuan, Y. Q., Li, F., Dong, R. H., Chen, J. S., He, G. S., et al. (2017). The development of a chinese healthy eating index and its application in the general population. *Nutrients.* 9, 977. doi: 10.3390/nu9090977

Zhai, F. Y., Du, S. F., Wang, Z. H., Zhang, J. G., Du, W. W., Popkin, B. M., et al. (2014). Dynamics of the Chinese diet and the role of urbanicity, 1991–2011. *Obes. Rev.* 15, 16–26. doi: 10.1111/obr.12124

Zhou, Y., Du, S., Su, C., Zhang, B., Wang, H., Popkin, B. M., et al. (2015). The food retail revolution in China and its association with diet and health. *Food Policy* 55, 92–100. doi: 10.1016/j.foodpol.2015.07.001

frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 13 June 2023
DOI 10.3389/fsufs.2023.1120757

Check for updates

OPEN ACCESS

EDITED BY
Amos Laar,
University of Ghana, Ghana

REVIEWED BY
Federica Aureli,
National Institute of Health (ISS), Italy

*CORRESPONDENCE
Shalander Kumar
✉ shalander.kumar@icrisat.org

RECEIVED 10 December 2022
ACCEPTED 22 May 2023
PUBLISHED 13 June 2023

CITATION
Kumar S, Das A, Kasala K and Ridoutt BG (2023) Shaping food environments to support sustainable healthy diets in low and middle-income countries.
Front. Sustain. Food Syst. 7:1120757.
doi: 10.3389/fsufs.2023.1120757

Shaping food environments to support sustainable healthy diets in low and middle-income countries

Shalander Kumar[1]*, Abhishek Das[1], Kavitha Kasala[1] and Bradley George Ridoutt[2,3]

[1]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India,
[2]Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, ACT, Australia,
[3]Department of Agricultural Economics, University of the Free State, Bloemfontein, South Africa

The global ambitions to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture demand a complex transition of the current food environments for enabling sustainable healthy diets. The food environments in Low and Middle-Income Countries (LMICs) have been experiencing rapid and dynamic transitions across the globe, necessitating a system-level thinking and systemic approach to understand opportunities for improvement. There is a need for valid, reliable measures of food and nutrition environments for reorienting thinking and data collection toward determinants of food demand, especially the food environment components, which are critical to understand the transforming food systems. Food environment transformations are urgently required to provide consumers with more affordable and nutritious diets capable of meeting social and environmental challenges. In the present perspective, we aim to provide insights on prioritizing research on understanding and designing evidence based inclusive food environments which is crucial for promoting long-term food system innovations that are economically, socially, and environmentally sustainable and, above all, contribute to sustainable healthy diets.

KEYWORDS

food environment, framework, sustainable healthy diet, low and middle-income countries (LMICs), food system

Introduction

During the past few decades, the food system dynamics in low and middle-income countries (LMICs) have been evolving rapidly. The Global Panel on Agriculture and Food Systems for Nutrition (GLOPAN), the United Nations (UN) High-Level Panel of Experts on Food Security and Nutrition (HLPE), and several recent studies and landmark reports (UNICEF., 2021; WFP, 2022) emphasize an immediate need to transform food systems which are currently broken. The current food systems are unable to provide sustainable and adequate nutrition equitably mainly due to disorganized agricultural intensification, over emphasis on industrialization and commercialization of food with inadequate priority to address food insecurity and malnutrition, equitable access to food, resource and environmental degradation, and changing consumer behavior. To overcome these challenges, a robust analytical framework applicable to food systems and their components is needed to design and implement appropriate interventions that will promote sustainable production, equitable food distribution, and address nutrition deficiency and hunger, especially in the developing countries.

There is need to undertake extensive studies to understand complex linkages within the food systems and their components. Such evidence base would be critical to design interventions to improve the broken food systems. According to the existing literature, the food system consists of four broad components: stakeholders of food systems, domains of food systems, drivers of food systems, and outcomes of food systems (High Level Panel of Experts on Food Security Nutrition., 2017; De Brauw et al., 2019). The food environment[1] is one of the core components under the domain of the food systems. Therefore, research to better understand the food environment is imperative to fix the broken food systems, especially in the context of the first action area-sustainable, resilient food systems for healthy diets, of the UN Decade of Action on Nutrition 2016–2025[2]. However, in practice, hardly any systematic information is available on the food environments, especially in LMICs. A lack of integration of such knowledge and perspective makes the relevant policies much weaker. Therefore, enabling a deeper understanding of the food environments is increasingly becoming essential to elucidate its complexities and improve diets and address malnutrition.

The aim of this perspective is to strengthen the narrative around importance of building evidence based inclusive food environments. Objectives of this perspective are 2 fold; first is to see briefly the areas on which researchers are working to understand and improve the food environment in LMICs and the second is to identify the priorities for food environment research for development in LMICs.

Following this brief introduction, we have discussed the brief overview of existing research on food environments and then we have discussed the need to prioritize the food environment research in the next section, followed by conclusions.

Brief overview of existing research areas on the food environment in LMICs

Some research has been conducted on the topic of food environments in LMICs over the past couple of decades, with a focus on understanding the intricate interplay between various factors and their impact on individual people and communities. This research has shed light on the complex challenges that the communities in LMICs face when it comes to accessing healthy and affordable food, and also highlights factors that contribute to food insecurity and malnutrition.

To gain a deeper comprehension of research on food environments, we can categorize it into two primary areas[3]: (a) Research on facts and frameworks to understand food environment interactions; (b) Research on policy interventions to improve food environments.

Both areas of research are important for understanding and addressing the complex and multifaceted challenges of the food environments in LMICs. In the following section we briefly discuss the major work streams under these categories:

Facts and frameworks to understand the food environment interactions

To promote a unified approach to food environment research, policies, and interventions, various authors have developed conceptual frameworks (Kanter et al., 2015; Turner et al., 2018, 2020; Downs et al., 2020; Bogard et al., 2021; Constantinides et al., 2021; Osei-Kwasi et al., 2021; Toure et al., 2021). These frameworks offer a clear and concise visual representation that links theoretical concepts with empirical research, enabling us to better comprehend the connections and relationships between food environment concepts, food choice, and nutrition and health outcomes. A comprehensive and flexible food environment framework allows us to evaluate the impact of physical, economic, political, and sociocultural contexts on people's interactions with the food system. It enables us to better understand how individuals make decisions about obtaining, preparing, and consuming food (Herforth and Ahmed, 2015; Downs et al., 2020; Lingham et al., 2022). The food environment framework offers valuable insights into the underlying factors that drive food consumption patterns. This framework also sheds light on the various pathways that influence food acquisition and consumption (Chen and Antonelli, 2020; Turner, 2020). Along with this framework, developing, testing, and validating standardized instruments and metrics to profile food environments in LMICs is crucial for understanding the diverse, complex and dynamic food environment that exists in these contexts. These standardized instruments and metrics can provide a comprehensive picture of the food environment by measuring and analyzing key indicators of food availability, accessibility, affordability, and quality (Ahmed et al., 2021). This can lead to informed evidence-based policies and interventions aimed at improving food security and nutrition outcomes (Ohri-Vachaspati and Leviton, 2010; Johnston et al., 2014; Herforth and Ahmed, 2015; Nguyen B. et al., 2021). Monitoring environmental footprints across the food systems is a crucial component of understanding the governance of food environments as the production, processing, transportation, and consumption of food are major drivers of environmental degradation and climate

1 Food environments are the physical, economic, political, and sociocultural contexts in which people engage with the food system to make their decisions about acquiring, preparing, and consuming food. Therefore, food environments are spaces in which people make decisions about food. Food environments determine the availability, accessibility, affordability, and desirability of different foods. They are the interface between individuals and the broader physical, economic, political, and sociocultural drivers of the food system (Swinburn et al., 2013; Turner et al., 2018).

2 https://www.who.int/docs/default-source/nutritionlibrary/departmental-news/mid-term-review—un-decade-of-action-on-nutrition/nutrition-decade-mtr-foresight-paper-en.pdf?sfvrsn=c3c14085_4

3 Basic structure of this distribution has been adopted from the Laar et al. (2022). It may be noted that neither this list is an exhaustive list, nor the cited literature is exhaustive one. Objective was to broadly identify the current research areas which help us to discuss the future priority areas of research with more clarity.

change, and can have significant impacts on the availability, accessibility, and affordability of nutritious foods (Kennedy et al., 2021).

Understanding consumer behavior is critical to identify the factors that influence consumers' choices in the context of local food environments and digital food environments[4]. The drivers of consumer behavior in these environments include individual, social, and environmental factors such as culture, personal preferences, social norms, convenience, and accessibility (Granheim et al., 2022; Turner et al., 2022). These factors influence consumers' livelihood and nutrition by shaping their food choices and dietary patterns. The local food environment provides consumers with access to fresh and healthy foods, while digital food environments offer convenience and accessibility (Granheim et al., 2022; Turner et al., 2022). Further, the commercial determinants of nutrition and health are important factors that influence individuals' dietary choices, particularly in LMICs. These determinants include the food industry's marketing and advertising practices, the availability and affordability of unhealthy foods, and the influence of multinational corporations (Clapp, 2021; Granheim et al., 2022). In LMICs there is growing evidence of associations between unhealthy/ultra-processed foods (added sugars, salt, and unhealthy fats) and the dietary, nutrition, and health outcomes. The negative health impacts of unhealthy/ultra-processed foods are of particular concern in LMICs, where rates of non-communicable diseases are increasing rapidly, and often multiple forms of malnutrition coexists within the populations (Popkin and Ng, 2022), especially in the child and young population (Carducci et al., 2021). Fast food marketing is successfully reaching children in developing and emerging economies using similar techniques as in developed economies (Witkowski, 2007). Children are heavily exposed to food marketing, particularly on television, promoting unhealthy, highly processed foods with appealing branding. This poses a significant danger to public health (Harris et al., 2009). Besides this formal sector, the informal sector plays a crucial role in shaping local food environments in LMICs. This sector encompasses various unregulated and non-formal economic activities, such as street vending, home-based food processing, and small-scale farming (Nguyen T. et al., 2021).

Research on policy interventions to improve food environments

The policy research related to food environments has to be primarily centered around ensuring that people have access to food and beverages that are safe, healthy, and convenient. The research on food environment policies can be conveniently classified into two categories: the first focuses on policy interventions at the individual and community levels, while the second investigates policy interventions at the macro (province or national) level.

Policy research at community/individual level

The development of effective strategies for promoting healthy diets (World Health Organization, 2019) is critical for reducing the burden of diet-related chronic diseases. Multiple strategies are needed at different levels to promote healthy diets and reduce the prevalence of diet-related chronic diseases in the communities. One approach that has been suggested is the use of nudges, which can encourage consumers to make healthier food choices in various commercial and institutional settings (Ruben et al., 2020). At the community level, it is important to raise awareness about the benefits of consuming locally generated nutritious foods while also highlighting the potential harms of consuming processed and ultra-processed foods (Herforth and Ahmed, 2015). Communities can also ensure access to safe, healthy, and convenient foods and beverages, particularly for individuals who have limited food preparation time (Brouwer et al., 2021). Identifying community-level priorities for their local food environments and establishing public-private partnerships to serve these needs can also be effective in promoting healthy diets (Thow et al., 2018; Yu et al., 2018). Furthermore, local governments can play a significant role in discouraging the consumption of low-cost and unhealthy processed foods through policies and regulations, as demonstrated by Mozaffarian et al. (2018) and Aylward et al. (2022).

Policy research at macro level

Transforming food environments requires cross-sectoral policy actions and convergence pathways to address the challenges posed by the triple burden of malnutrition. One of the first steps toward this goal is mapping community food environments and identifying community-level context-specific nutrition and dietary policy and implementation strategy. These strategies can be developed and implemented at the community level through collaborations between various stakeholders such as policymakers, public health experts, and community members (Baker et al., 2020; Laar et al., 2020, 2022). Fiscal policy can play a critical role in promoting healthy diets by offering subsidies to producers or consumers of healthy food and imposing taxes on unhealthy food. For instance, subsidies on fruits, vegetables, and whole grains can help to lower their price and increase their accessibility, while taxes on sugary drinks, snacks, and other unhealthy foods can discourage their consumption. Such policy measures can improve accessibility to healthy and sustainable diets, thereby contributing to reducing the prevalence of malnutrition. However, it is important to assess the impact of such measures on the triple burden of malnutrition, including undernutrition, overweight and obesity, and micronutrient deficiencies. This requires a comprehensive evaluation of the direct and indirect effects of fiscal policy on food prices, consumption patterns, and health outcomes (Gómez et al., 2013; DeFries et al., 2018; Mockshell et al., 2021). To evaluate the effectiveness of interventions, there is need to conduct robust longitudinal and experimental studies at multiple scales that assess the multi-dimensional impact on diets,

4 Digital food environments are the online settings through which flows of services and information that influence people's food and nutrition choices and behavior are directed. They encompass a range of elements, including social media, digital health promotion interventions, digital food marketing and online food retail (World Health Organization, 2021a).

nutrition status, and health outcomes. Such studies can provide critical evidence on the effectiveness of different interventions and would help policymakers to design evidence-based policies that can lead to better health outcomes (Keats et al., 2019; Turner et al., 2020). Furthermore, effective nutrition literacy policies can increase awareness and encourage healthier diets across commercial and institutional channels, as well as locally generated healthy nutritious food. Nutrition literacy policies can include nutrition education programs, labeling requirements, and nutrition information campaigns that target different population groups. These policies can help to improve food choices and eating habits by promoting healthy and sustainable diets (Aldaya et al., 2021; World Health Organization, 2021b). Finally, it is important to identify and promote innovations that stimulate demand for sustainable and healthy diets. These innovations can include new products, services, and business models that promote healthy and sustainable food consumption. For instance, food delivery services that provide healthy and sustainable meals can increase accessibility to healthy food and reduce the need for unhealthy food options (Dwivedi et al., 2017; De Brauw et al., 2019). By adopting these cross-sectoral policy actions and convergence pathways, it is possible to transform food environments and reduce the prevalence of malnutrition.

Need to prioritize the food environment research

LMICs' food environments are undergoing rapid changes, presenting a massive challenge to food environment research. The assessment, monitoring, and evaluation of food environments and the implementation relevant policies in LMICs is a complex task due to the lack of standardized metrics and methods, proper data and implementation strategy. Instruments specific to the LMICs' settings are still under development, as the unique and multifaceted nature of their food environments makes it challenging to establish common terms and definitions. Hence there is a need for prioritizing the food environment research specially in the following the areas:

Development of measurable holistic framework

The food environments in LMICs are influenced by a wide range of complex variables that include seasonal cycles, economic and climate shocks, gender and social biases, cultural circumstances, conflicts, infrastructural disparity, the multiplicity of supply chain actors, religion, policy, education, networks, and human capital and weak institutions. Along with these factors, the presence of various food sources, such as market-based vendors, informal food vendors, and non-market-based food sources, and the small scale of food businesses, add another layer of complexity to the research. Even though many frameworks have been developed for describing or understanding relationships between agriculture and nutrition, they have often been oriented toward project design and implementation or focus on sub-sections of the food environment without adequate attention to big-picture linkages which are frequently needed for consideration by policymakers. Effective policies to transform food systems cannot be designed and implemented without a holistic understanding of the food environments. These factors make the food environment in LMICs distinctly different from high-income countries (HICs) and require a specialized approach to understand and assess them. The lack of standardized metrics and the presence of various non-measurable variables further exacerbate the complexity of researching the food environment in LMICs.

Hence there is a need for a comprehensive structural framework that allows an interdisciplinary approach to understanding the interactions among different domains and elements of food environments and the food system to promote effective interventions to improve nutrition and health outcomes in these settings.

Collection of comprehensive and reliable data

The availability and reliability of data are critical for understanding the food environment in LMICs. Unfortunately, there is a significant lack of coherent data on various dimensions of the food environment in these settings. The lack of reliable data on logistics, storage, and marketing is a significant issue in LMICs. Detailed datasets that contain geotagged information about food vendors are also limited, if not entirely non-existent. This lack of data makes it difficult to assess the location and density of food outlets in a given area and hinders efforts to identify food deserts or other areas that lack access to healthy food options.

Additionally, food and nutrition regulations and documentation may be less readily available in LMICs. The lack of regulatory oversight and documentation makes it difficult to monitor the quality of food sold in markets and restaurants, leading to a higher risk of foodborne illnesses and other health problems. The absence of reliable data also makes it challenging to assess the impact of various interventions aimed at improving the food environment in LMICs.

Furthermore, the absence of data on the food environment in LMICs can lead to a lack of political will to make changes in the food system. Inadequate data can also hinder efforts to secure funding for food-related research and interventions.

Therefore, it is essential to prioritize the collection of comprehensive and reliable data over time on various dimensions of the food environment in LMICs. This data should include information on the location and density of food outlets, the availability of healthy food options, food safety, quality, and food and nutrition regulations. Collecting this data will enable policymakers, researchers, and stakeholders to better understand the food environment in LMICs, and develop evidence-based interventions, and ultimately promote positive nutrition and health outcomes in these settings.

Policy implementation strategy

Suitable policy development can be one of the most important instruments to improve the food environment in the LMICs. However, policymakers and researchers often face significant challenges in designing and implementing appropriate policies in the field due to the highly diverse contexts of LMICs. This is particularly true when it comes to food-related policies, as the food environment is influenced by a multitude of factors, including social, cultural, religion, economic conditions, and political stability.

To successfully implement policies aimed at improving the food environment in LMICs, it is necessary to develop a comprehensive implementation strategy that takes into account the unique challenges faced by extension agents in the field. These challenges may include limited resources, cultural barriers, and logistical difficulties. Without proper research on the implementation strategy, policy development may fail to yield the desired outcomes.

Furthermore, it is essential to involve local communities and stakeholders in the policy development and implementation process. The involvement of these groups can help to ensure that policies are culturally appropriate and meet the needs of local populations. It can also help to build trust between policymakers and local communities, and facilitate the successful implementation of policies.

Research on effective policy implementation in LMICs requires a holistic approach that takes into account the complex and diverse nature of the food environment. This approach should involve robust research on implementation strategies, appropriate business models for engaging local communities and stakeholders, and a commitment to building strong partnerships among policymakers, researchers, and extension agents.

Conclusions

This perspective builds a narrative that there is an urgent need for systematic research to understand the complex interactions and connections among different elements of the food environment and the broader food system to achieve sustainable healthy diets in LMICs. The current understanding of the food environment in LMICs is still in its early stages. We argue that the future research need to promote a comprehensive structural framework that allows an understanding of interactions among different domains, generating coherent evidence monitored through key performance indicators and developing evidence based actionable policies for implementation to improve the food environments. It needs to integrate qualitative and quantitative findings to develop new hypotheses and refine ongoing studies. By doing so, policymakers can develop effective policies that can improve the food environment and promote sustainable positive nutrition and health outcomes. The conceptual nature of our proposition is its limitation and it can continue to evolve when implemented on the ground in the LMICs.

Author contributions

SK: conceptualization, review and editing, supervision, and funding acquisition. AD and KK: conceptualization and original draft. BR: review and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by Indian Council of Agricultural and CRP Grain Legumes and Dryland Cereals (GLDC) through CGIAR Fund Donors and bilateral funding agreements.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Ahmed, S., Kennedy, G., Crum, J., Vogliano, C., McClung, S., and Anderson, C. (2021). Suitability of data-collection methods, tools, and metrics for evaluating market food environments in low-and middle-income countries. *Foods.* 10, 2728. doi: 10.3390/foods10112728

Aldaya, M.M., Ibañez, F.C., Domínguez-Lacueva, P., Murillo-Arbizu, M.T., Rubio-Varas, M., Soret, B., et al. (2021). Indicators and recommendations for assessing sustainable healthy diets. *Foods.* 10, 999. doi: 10.3390/foods10050999

Aylward, B.L., Milford, K.M., Storey, K.E., Nykiforuk, C.I., and Raine, K.D. (2022). Local Environment Action on Food project: impact of a community-based food environment intervention in Canada. *Health Promot. Int.* 37, 127. doi: 10.1093/heapro/daab127

Baker, P., Machado, P., Santos, T., Sievert, K., Backholer, K., Hadjikakou, M., et al. (2020). Ultra-processed foods and the nutrition transition: Global, regional and national trends, food systems transformations and political economy drivers. *Obes. Rev.* 21, 13126. doi: 10.1111/obr.13126

Bogard, J.R., Andrew, N.L., Farrell, P., Herrero, M., Sharp, M.K., and Tutuo, J. (2021). A typology of food environments in the pacific region and their relationship to diet quality in solomon islands. *Foods.* 10, 2592. doi: 10.3390/foods10112592

Brouwer, I.D., van Liere, M.J., de Brauw, A., Dominguez-Salas, P., Herforth, A., Kennedy, G., et al. (2021). Reverse thinking: taking a healthy diet perspective towards food systems transformations. *Food Secur.* 13, 1497–1523. doi: 10.1007/s12571-021-01204-5

Carducci, B., Oh, C., Roth, D.E., Neufeld, L.M., Frongillo, E.A., L'Abbe, M.R., et al. (2021). Gaps and priorities in assessment of food environments for children and adolescents in low-and middle-income countries. *Nature Food.* 2, 396–403. doi: 10.1038/s43016-021-00299-5

Chen, P.J., and Antonelli, M. (2020). Conceptual models of food choice: influential factors related to foods, individual differences, and society. *Foods.* 9, 1898. doi: 10.3390/foods9121898

Clapp, J. (2021). The problem with growing corporate concentration and power in the global food system. *Nature Food.* 2, 404–408. doi: 10.1038/s43016-021-00297-7

Constantinides, S.V., Turner, C., Frongillo, E.A., Bhandari, S., Reyes, L.I., and Blake, C.E. (2021). Using a global food environment framework to understand relationships with food choice in diverse low-and middle-income countries. *Glob. Food Sec.* 29, 100511. doi: 10.1016/j.gfs.2021.100511

De Brauw, A., Brouwer, I.D., Snoek, H., Vignola, R., Melesse, M.B., Lochetti, G., et al. (2019). Food system innovations for healthier diets in low and middle-income countries. Intl. *Food Policy Res. Inst*. 1816, 1–39. doi: 10.2499/p15738coll2.133156

DeFries, R., Chhatre, A., Davis, K. F., Dutta, A., Fanzo, J., Ghosh-Jerath, S., et al. (2018). Impact of historical changes in coarse cereals consumption in India on micronutrient intake and anemia prevalence. *Food Nutr. Bull.* 39, 377–392. doi: 10.1177/0379572118783492

Downs, S.M., Ahmed, S., Fanzo, J., and Herforth, A. (2020). Food environment typology: advancing an expanded definition, framework, and methodological approach for improved characterization of wild, cultivated, and built food environments toward sustainable diets. *Foods.* 9, 532. doi: 10.3390/foods9040532

Dwivedi, S.L., Van Bueren, E.T.L., Ceccarelli, S., Grando, S., Upadhyaya, H.D., and Ortiz, R. (2017). Diversifying food systems in the pursuit of sustainable food production and healthy diets. *Trends Plant Sci.* 22, 842–856. doi: 10.1016/j.tplants.2017.06.011

Gómez, M.I., Barrett, C.B., Raney, T., Pinstrup-Andersen, P., Meerman, J., Croppenstedt, A., et al. (2013). Post-green revolution food systems and the triple burden of malnutrition. *Food Policy.* 42, 129–138. doi: 10.1016/j.foodpol.2013.06.009

Granheim, S.I., Løvhaug, A.L., Terragni, L., Torheim, L.E., and Thurston, M. (2022). Mapping the digital food environment: a systematic scoping review. *Obesity Rev.* 23, e13356. doi: 10.1111/obr.13356

Harris, J.L., Brownell, K.D., and Bargh, J.A. (2009). The food marketing defense model: integrating psychological research to protect youth and inform public policy. *Soc. Issues Policy Rev.* 3, 211–271. doi: 10.1111/j.1751-2409.2009.01015.x

Herforth, A., and Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Secur.* 7, 505–520. doi: 10.1007/s12571-015-0455-8

High Level Panel of Experts on Food Security and Nutrition. (2017). Nutrition and Food Systems. A report by the High Level Panel of Experts on Food security and Nutrition of the Committee on World Food Security, Rome, Italy.

Johnston, J.L., Fanzo, J.C., and Cogill, B. (2014). Understanding sustainable diets: a descriptive analysis of the determinants and processes that influence diets and their impact on health, food security, and environmental sustainability. *Adv. Nutr.* 5, 418–429. doi: 10.3945/an.113.005553

Kanter, R., Walls, H.L., Tak, M., Roberts, F., and Waage, J. (2015). A conceptual framework for understanding the impacts of agriculture and food system policies on nutrition and health. *Food Secur.* 7, 767–777. doi: 10.1007/s12571-015-0473-6

Keats, E.C., Neufeld, L.M., Garrett, G.S., Mbuya, M.N., and Bhutta, Z.A. (2019). Improved micronutrient status and health outcomes in low-and middle-income countries following large-scale fortification: evidence from a systematic review and meta-analysis. *Am. J. Clin. Nutr.* 109, 1696–1708. doi: 10.1093/ajcn/nqz023

Kennedy, E., Webb, P., Block, S., Griffin, T., Mozaffarian, D., and Kyte, R. (2021). Transforming food systems: the missing pieces needed to make them work. *Curr. Dev. Nutr. 5*, nzaa177. doi: 10.1093/cdn/nzaa177

Laar, A., Barnes, A., Aryeetey, R., Tandoh, A., Bash, K., Mensah, K., et al. (2020). Implementation of healthy food environment policies to prevent nutrition-related non-communicable diseases in Ghana: national experts' assessment of government action. *Food Policy.* 93, 101907. doi: 10.1016/j.foodpol.2020.101907

Laar, A.K., Addo, P., Aryeetey, R., Agyemang, C., Zotor, F., Asiki, G., et al. (2022). Perspective: food environment research priorities for africa—lessons from the africa food environment research network. *Adv. Nutr.* 13, 739–747. doi: 10.1093/advances/nmac019

Lingham, S., Manning, L., and Maye, D. (2022). Reimagining food: readdressing and respecting values. *Sustainability.* 14, 7328. doi: 10.3390/su14127328

Mockshell, J., Asante-Addo, C., Andam, K.S., and Asante, F.A. (2021). Transitioning to nutrition-sensitive food environments in Ghana: Triple sector strategies to reduce the triple burden of malnutrition. *Intl Food Policy Res Inst*. 2038, 1–52. doi: 10.2499/p15738coll2.134522

Mozaffarian, D., Angell, S.Y., Lang, T., and Rivera, J.A. (2018). Role of government policy in nutrition—barriers to and opportunities for healthier eating. *BMJ.* 361, k2426. doi: 10.1136/bmj.k2426

Nguyen, B., Cranney, L., Bellew, B., and Thomas, M. (2021). Implementing food environment policies at scale: what helps? *what hinders? a systematic review of barriers and enablers. Int. J. Environ. Health Res.* 18, 10346. doi: 10.3390/ijerph181910346

Nguyen, T., Pham Thi Mai, H., van den Berg, M., Huynh Thi Thanh, T., and Béné, C. (2021). Interactions between food environment and (Un) healthy consumption: Evidence along a rural-urban transect in viet nam. *Agriculture.* 11, 789. doi: 10.3390/agriculture11080789

Ohri-Vachaspati, P., and Leviton, L. C. (2010). Measuring food environments: a guide to available instruments. *Am. J. Health Promot.* 24, 410–426. doi: 10.4278/ajhp.080909-LIT-190

Osei-Kwasi, H.A., Laar, A., Zotor, F., Pradeilles, R., Aryeetey, R., Green, M., et al. (2021). The African urban food environment framework for creating healthy nutrition policy and interventions in urban Africa. *PLoS ONE.* 16, e0249621. doi: 10.1371/journal.pone.0249621

Popkin, B.M., and Ng, S.W. (2022). The nutrition transition to a stage of high obesity and noncommunicable disease prevalence dominated by ultra-processed foods is not inevitable. *Obesity Rev.* 23, 13366. doi: 10.1111/obr.13366

Ruben, R., Grace, D., and Lundy, M. (2020). Supporting consumer choices toward healthy, safe, and sustainable diets in low-and middle-income countries. *Intl Food Policy Res Inst.* 1–4. doi: 10.2499/p15738coll2.133955

Swinburn, B., Vandevijvere, S., Kraak, V., Sacks, G., Snowdon, W., Hawkes, C., et al. (2013). Monitoring and benchmarking government policies and actions to improve the healthiness of food environments: a proposed government healthy food environment policy index. *Obesity Rev.* 14, 24–37. doi: 10.1111/obr.12073

Thow, A.M., Verma, G., Soni, D., Soni, D., Beri, D.K., Kumar, P., et al. (2018). How can health, agriculture and economic policy actors work together to enhance the external food environment for fruit and vegetables? A qualitative policy analysis in India. *Food Policy.* 77, 143–151. doi: 10.1016/j.foodpol.2018.04.012

Toure, D., Mbuya, M., Herforth, A., Pelto, G., and Neufeld, L. (2021). An Emergent Measurement Framework of the Market Food Environment in Low-and Middle-Income Countries (OR21-08-19). *Current Developments in Nutrition.* 3(Supplement_1), 034-OR21. doi: 10.1093/cdn/nzab023

Turner, C. (2020). *Investigating food environments and drivers of food acquisition in low-and middle-income countries: The case of peri-urban Hyderabad, Telangana, India (Doctoral* dissertation). London School of Hygiene and Tropical Medicine.

Turner, C., Aggarwal, A., Walls, H., Herforth, A., Drewnowski, A., Coates, J., et al. (2018). Concepts and critical perspectives for food environment research: a global framework with implications for action in low-and middle-income countries. *Glob. Food Sec.* 18, 93–101. doi: 10.1016/j.gfs.2018.08.003

Turner, C., Bhogadi, S., Walls, H., Surendran, S., Kulkarni, B., Kinra, S., et al. (2022). Drivers of food acquisition practices in the food environment of peri-urban Hyderabad, India: A qualitative investigation. *Health Place.* 74, 102763. doi: 10.1016/j.healthplace.2022.102763

Turner, C., Kalamatianou, S., Drewnowski, A., Kulkarni, B., Kinra, S., and Kadiyala, S. (2020). Food environment research in low-and middle-income countries: a systematic scoping review. *Adv. Nutr.* 11, 387–397. doi: 10.1093/advances/nmz031

UNICEF. (2021). The state of food security and nutrition in the world 2021.Valenzuela, M.J. (2021). *The Impacts of Sugar Taxation Policies on Oral Health: A Mixed Methods Study.* Doctoral dissertation, University of York.

WFP, WHO, and UNICEF. (2022). *The state of food security and nutrition in the world* 2022.

Witkowski, T. H. (2007). Food marketing and obesity in developing countries: analysis, ethics, and public policy. *J. Macromarketing.* 27, 126–137. doi: 10.1177/0276146707300076

World Health Organization (2019). *Sustainable healthy diets*: *Guiding principles.* Food and Agriculture Org.

World Health Organization (2021a). Digital food environments Factsheet. Available online at: https://apps.who.int/iris/bitstream/handle/10665/342072/WHO-EURO-2021-2755-42513-59052-eng.pdf?sequence=1andisAllowed=y#:$\sim$:text=Digital%20food%20environments%20are%20the,choices%20and%20behaviour%20are%20directed

World Health Organization (2021b). *Action framework for developing and implementing public food procurement and service policies for a healthy diet.*

Yu, Y., Osei-Kyei, R., Chan, A.P.C., Chen, C., and Martek, I. (2018). Review of social responsibility factors for sustainable development in public–private partnerships. *Sustainable Development.* 26, 515–524. doi: 10.1002/sd.1737

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 08 September 2023
DOI 10.3389/fsufs.2023.1090690

Check for updates

OPEN ACCESS

EDITED BY
Aida Turrini,
Independent researcher, Scansano, Italy

REVIEWED BY
Mauricio Gonzalez-Chang,
Austral University of Chile, Chile
Anne Lauvie,
INRAE Occitanie Montpellier, France

*CORRESPONDENCE
Erin M. Silva
✉ emsilva@wisc.edu

†These authors share first authorship

RECEIVED 05 November 2022
ACCEPTED 22 August 2023
PUBLISHED 08 September 2023

CITATION
Silva EM, Wezel A, Stafford C, Brives J, Bosseler N, Cecchinato N, Cossement C, Ranaldo M and Broome M (2023) Insights into agroecological farming practice implementation by conservation-minded farmers in North America.
Front. Sustain. Food Syst. 7:1090690.
doi: 10.3389/fsufs.2023.1090690

Insights into agroecological farming practice implementation by conservation-minded farmers in North America

Erin M. Silva[1*†], Alexander Wezel[2†], Caley Stafford[2], Jeanne Brives[2], Nathan Bosseler[2], Nicole Cecchinato[2], Camille Cossement[2], Marzia Ranaldo[2] and Megan Broome[1]

[1]Department of Plant Pathology, University of Wisconsin-Madison, Madison, WI, United States,
[2]Agroecology and Environment Research Unit, ISARA, Lyon, France

Introduction: The transformation of our food system towards a more resilient agroecological framework is one of the most pressing needs faced by our global community. Understanding the use of multiple conservation practices is important in the development of research, education, and policy to accelerate their more widespread integration of into farming systems.

Methods: The aim of this study was to conduct a preliminary investigation of the trends regarding multiple practice adoption of conservation farming practices by conventional and organic farmers engaging with sustainable farming methods. Forty farmers were interviewed regarding their use of conservation practices, as well as their motivations, barriers, and future plans for new implementation and expansion of current practices.

Results: Farmers spontaneously identified cover crops and vegetation strips as the most frequently used conservation practices; however, upon more specific inquiry, we found that more than 50% of farmers used additional agroecological conservation practices including local crop varieties, intercropping, managed grazing, crop rotations, and no-till, with many farmers using multiple practices. Overall, we found no correlation of organic certification with the number of conservation practices implemented by farmers. The major motivations towards the adoption of practices included improved soil quality and profitability. Main identified barriers included financial means and risk, lack of knowledge, and access to resources. Farmers showed interest in further implementation of additional conservation practices, including expanded use of cover crops, tree plantings, and no-till practices.

Discussion: Further understanding complementarities, as well as differences in barriers and motivations, can contribute to the design of effective education strategies and financial incentives to promote the simultaneous implementation of agroecological conservation practices.

KEYWORDS

sustainable agriculture, cover crops, agroecology, farmer practice adoption, conservation measures, soil quality, intercropping, no-till

1. Introduction

The transformation of our food system into a more resilient agroecological framework is one of the most pressing needs faced by our global community. As climate extremes and unpredictability continue to become more frequent and widespread, the persistent challenges of soil and biodiversity loss which result from our current agricultural production practices will only become more pronounced (Jat et al., 2014; Findlater et al., 2019). Alternative practices are being sought that can alleviate agroecosystem vulnerabilities such as soil erosion, soil and water quality degradation, excess or insufficient water quantity, degraded plant condition, soil carbon loss, livestock production limitation, inadequate fish and wildlife habitat, inefficient energy use, and air quality impacts (USDA Natural Resources Conservation Service – USDA NRCS, 2013).

Certain agricultural practices have been identified that promote the resilience of our cropping systems while enhancing environmental and societal outcomes. Many of these practices have been described using different terminology, such as agroecological practices, environmentally friendly practices, conservation agriculture, and more recently, regenerative agriculture. In particular, the term agroecological practices is increasingly used throughout the globe (Wezel et al., 2014; Wezel and Silva, 2017; Paracchini et al., 2020). However, in the United States, the most codified of these definitions is the term "conservation practices," where individual practices may have direct associations to incentive programs administered by USDA NRCS (2013). Typical conservation practices promoted by NRCS programs include no-till, reduced-till, cover crops, contour buffer strips, water retention structures, perennial plantings, nutrient management, terraces, waterways, filter strips, prairie establishment, wetland restoration, timber stand improvement, grade stabilization, feedlot runoff control, tree plantings, prescribed grazing, and bioreactors (Kuhn, 2018).

While incentive programs exist to promote the further implementation of conservation practices, adoption is still relatively limited in the United States. For example, cover crop acres included only 3.9% of all US cropland in 2017, with the highest adoption (29% of acres) in the mid-Atlantic states and lower adoption (1% of acres) in more arid states (Zulauf and Brown, 2019). No-till management, while more widely adopted than cover crops, is also implemented on only a minority of acres, with 26% of total cropland managed with these practices in 2017 (Sawadgo and Pastina, 2022).

In the context of agroecology, within which the recognition of the need to transform practices using a systems-based context rather than the more simplistic approach of assessing the value of a practice in isolation, there is a particular importance to understanding how farmers proceed with the sequential or simultaneous adoption of multiple conservation practices to maximize agroecosystem benefits. Multiple practices integrated in tandem can create synergies which enhance and improve the effectiveness ecosystem provisioning (Hatt et al., 2018; Debray et al., 2019; Boeraeve et al., 2020; Bezner Kerr et al., 2021). Not only can the implementation of different conservation practices promote the achievement of independent goals (e.g., reducing erosion, enhancing biodiversity, and improving water quality), but the resulting effects of coordinated practices can have synergistic effects beyond those of a single practice in isolation (Christianson et al., 2018).

Several previous studies have examined rates and motivations related to farmer adoption of individual conservation practices, such as cover crops (Moore et al., 2016; Lee and McCann, 2019); no-till management (Krause, 2017; Wade and Classen, 2017); or management-intensive grazing (Foltz and Lang, 2005; Wang et al., 2020; Winsten et al., 2020). Fewer studies have examined the joint or combined implementation of conservation practices (Canales et al., 2020; Gong et al., 2021). Liebert et al. (2022) documented common agroecological practices implemented by organic fruit and vegetable farms. Focused on eight agroecological practices (intercropping, use of compost, insectary planting, reduced tillage, cover cropping, crop rotation, riparian buffers, and border planting), the authors found that farmers who managed fewer acres were more likely to use multiple practices as compared with larger farm sizes. However, the probability of adoption of any specific practice varied depending on farm size, with larger farms more likely to adopt reduced tillage practices, and smaller farms were more likely to use intercropping, insectary planting, and border planting (results based on tendencies and not statistical significant differences). While these previous studies provide insights as to the characteristics of farms adopting specific conservation practices, knowledge gaps remain about motivation to adopt or not multiple conservation practices, but also challenges and barriers farmers identify or face for adopting such practices, particularly as these trends relate to farms that have already begun to explore the integration of these practices into their farming operations.

The aim of this study was to conduct a preliminary investigation using an exploratory interview dataset of farmers choices, preferences and combinations regarding the use of multiple agroecological conservation farming practices by farmers in the USA already utilizing some conservation practices, with some complementary data from Canada. Moreover, we investigate **(i)** if adoption of these practices might be influenced by financial support, being under organic certification, **(ii)** which are the drivers for farmers' motivation influencing the implementation of conservation practices as well as **(iii)** the barriers identified by farmers for adoption of practices. We specifically chose to focus on farmers with the US who already had a demonstrated level of commitment to an openness to using conservation practices as defined by the USDA NRCS, which allowed us to more deeply explore barriers, challenges, and motivations to multi-practice implementation that would lead for a more systems-based agroecological approach to conservation practice adoption. We documented the most frequently used practices by both organic and conventional farmers currently engaged with conservation cropping systems, as well as motivations, barriers, and goals for current and future implementation of practices. We chose to focus on farmers that had demonstrated a level of commitment to sustainability goals for their farms, thus enhancing our ability to begin to discern trends in the more complex implementation of multiple practices in tandem or in sequence. While this study is exploratory in nature, it provides new insights that can guide more comprehensive studies to understand the multiple underlying internal and external factors (e.g., pedo-climatic context, technical or financial barriers, farmers' knowledge, knowledge exchange, training, policies), and farmers' motivations leading to complementary and antagonistic practice adoption.

2. Methods

2.1. Sampling and data collection

This research employed a qualitative approach to understanding farmers' motivations for adopting conservation practices, as well as challenges and barriers to further implementation. A qualitative approach was chosen to develop a more nuanced understanding of the types of practices farmers were using and their experiences. The conservation practices chosen to highlight within the interviews were primarily those addressed with USDA Natural Resource Conservation Service (USDA NRCS) conservation programs, thus were practices more widely recognized by farmers. Data was collected through semi-structured interviews with farmers. Thirty to sixty minute interviews via phone or videoconference were conducted in October and November of 2021, with the conversations recorded.

Purposive and snowball sampling techniques were used to recruit participants representing farmers who already had an initial degree of commitment to the adoption of conservation practices. Initial interview participants were recruited through midwestern farmer networks focused on promoting organic and sustainable agricultural practices (e.g., UW-Madison's Organic Grain Resource and Information Network; Practical Farmers of Iowa; Wisconsin Department of Agriculture, Trade, and Consumer Protection-funded Farmer-led Watershed Groups). Further participants were recommended by other interviewees (Figure 1).

2.2. Data analysis

The interviews were split into five distinct sections: farm demographics; open-ended farmer-identified conservation practices; selection of conservation practices pre-determined within the interview structure; identification of practices currently use to control insect pests, diseases, and weeds; and motivation and barriers for future implementation of additional conservation practices. The nine pre-identified practices included: diversified crop rotation of four or more crops; cover crops; intercropping or interseeding (association of at least two crops grown simultaneously on the same field); cultivar mixtures; locally adapted/local crop varieties; no-till practices; biological control; vegetation strips on borders of or within the crop field; and managed grazing of livestock.

Demographic data and quantitative data were analysed with R software program using descriptive statistics and correlation analysis, and qualitative data was analysed through text coding based on common themes. The qualitative data regarding motivation and barriers for implementation were collected as text, analyzed, and then translated into quantitative data. First, the main themes of each interview were identified, and in a second step, similar themes across the different interviews were merged. In order to analyze the agricultural practices that were identified by the farmers, a key was created for uniformity of terminology to describe the practices (e.g., buffer strips and hedgerows were categorized as "vegetation strips" within the farmer identified practices).

3. Results and discussion

3.1. Demographic data

The interview pool including 40 farmers, primarily located in the upper midwestern USA. Most farmers interviewed (85%) identified themselves as the owner of the farm operation, with 15% identifying as the manager/operator (Table 1). Eighty-eight percent of the farmers were 36–65 years old, and 92.5% identified as male. Over half the farms (57.5%) ranged from 100–1,000 ha, 22.5% were smaller than 100 ha and 20% larger than 1,000 ha. Seventy-three percent of the farms described themselves as a family farm or a single-owner enterprise. The other farms belonged to multiple-owner enterprises. Most farms (62.5%) included livestock as part of their farm operation.

FIGURE 1
Geographic location of interviewed farmers.

TABLE 1 Demographic information of interviewed farmers ($n = 40$).

	Categories	%
Interviewee position	Owner	85
	Manager/operator	15
Farm size (ha)	0–10	7.5
	10–100	15
	100–1,000	57.5
	>1,000	20
Legal status	Family farm/single-owner enterprise	73
	Others	27
Farm type	Cereal grains/arable crops	22.5
	Mixed crops and livestock	62.5
	Other	15
Label or certification	None	45
	Organic	47.5
	Other (Rodale Institute Regenerative Organic Certification)	7.5
Age	18–35 years	5
	36–65 years	88
	>65 years	7
Gender	Male	92.5
	Female	7.5

Approximately half of the farms (47.5%) managed some or all their land as certified organic, with 7.5% certified under other labels such as the Rodale Institute Regenerative Organic Certification.

3.2. Conservation practices implementation

Farmers self-identified several conservation measures currently used on their farms (Figure 2). Cover crops (92.5%) were the most frequently mentioned practice, followed by vegetation strips (i.e., grass strips, waterways, flowering strips, and buffer strips) (65%), managed grazing (42.5%), crop rotation (40%), and no-till (40%).

When asked about the utilization of specific conservation practices which were predefined by the interviewers, similar trends were observed as with open-ended identification (Figure 3). The most frequently implemented practices included cover crops (97.5%), grass strips (85%), and local crop varieties (80%), followed by intercropping/interseeding (72.5%), and crop rotation (70%). Managed grazing, crop rotation, and no-till were also mentioned, ranging between 65%–70% of farmers using these practices. The highest percentage of the interviewees (35%) implemented six out of ten practices, while 22.5% implemented nine out of ten practices and 17.5% implemented seven out of ten practices. Only one farmer (2.5%) implemented all ten practices presented.

The trends regarding implementation of practices employed by the farmers in our sample differed from those reported from USDA Agricultural Resource Management Survey (ARMS) (Wade et al., 2015), with the adoption of conservation practices in our study being much greater. For example, no-till practices were used by 67.5% by interviewed farmers, compared to an average of 38% across USA farms reported by ARMS. Cover crop adoption was orders of magnitude greater in our sample as compared to the national average, with almost all farmers planting cover crops, whereas previous studies have documented that less than 3% of the agricultural land within the US is managed using cover crops (Hellerstein et al., 2019). Similarly, managed grazing was implemented more frequently across our sample, with 65% of farmers using this practice compared to 22% of conventional producers in 2012 as documented in a previous study (Hellerstein et al., 2019). This greater proportion of adoption by farmers in our sample may be due to the recruitment techniques used for this study, which drew from farmer organizations with emphases on alternative agriculture approaches, including opportunities to engage with education and peer groups related to conservation practice implementation.

The use of locally adapted varieties was self-identified by very few farmers as a conservation approach (2.5%); however, when asked directly, most farmers interviewed (80%) did confirm their use of this strategy. This discrepancy in answers could indicate that farmers did not associate the use locally adapted varieties with positive conservation outcomes, despite a broader recognition of the role of targeted crop breeding and selection in the mitigation of crop nutrient needs, pests, diseases, water use, and temperature responses (Banga and Kang, 2014). Farmer definitions of "locally adapted" varied widely, perhaps exacerbating the lack of association of the practices with conservation goals. Some farmers considered cultivars as local varieties when purchased through a local seed dealer. However, other farmers identified locally adapted varieties as those that had demonstrated superior performance in their environments through yield and performance trials. A few farmers chose varieties specifically bred for their environments. Each of these approaches could have a degree of positive impact on local adaptation and associated reduction of inputs due to superior crop performance contributing to its ability to better withstand local pest and disease pressures.

3.3. Crop protection practices

Farmers associated several of their conservation practices with benefitting pest management, including the use of cover crops and crop rotation (each cited by 50% of respondents) (Figure 4). Mechanical soil disturbance (e.g., tillage and cultivation) was also cited frequently (47.5%), likely due to its common use on organic farms for weed management. Managed grazing was also identified as a tool that benefitted pest management, again likely due to its role in weed management particularly on organic farms (27.5%). Chemical protection was only identified by 20% of the interviewees as a crop protection strategy; however, alternative forms of spraying (e.g., "natural"/"non-synthetic" spraying) were utilized for crop protection as well.

Strategies that promote beneficial insects (e.g., vegetative strips) were mentioned by only 10% of respondents, despite their relatively high adoption by the farmers interviewed. Interestingly, the farmers interviewed for this study did not associate vegetation strips with pest management, despite their documented effectiveness as

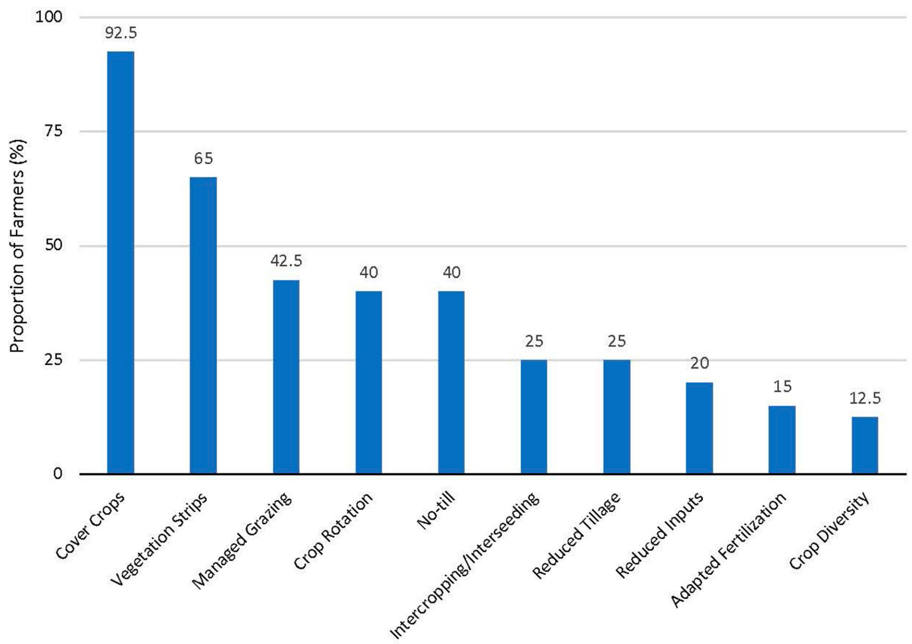


FIGURE 2
Agroecological conservation practices self-identified by farmers (practices are only shown if mentioned by at least 10% of farmers).

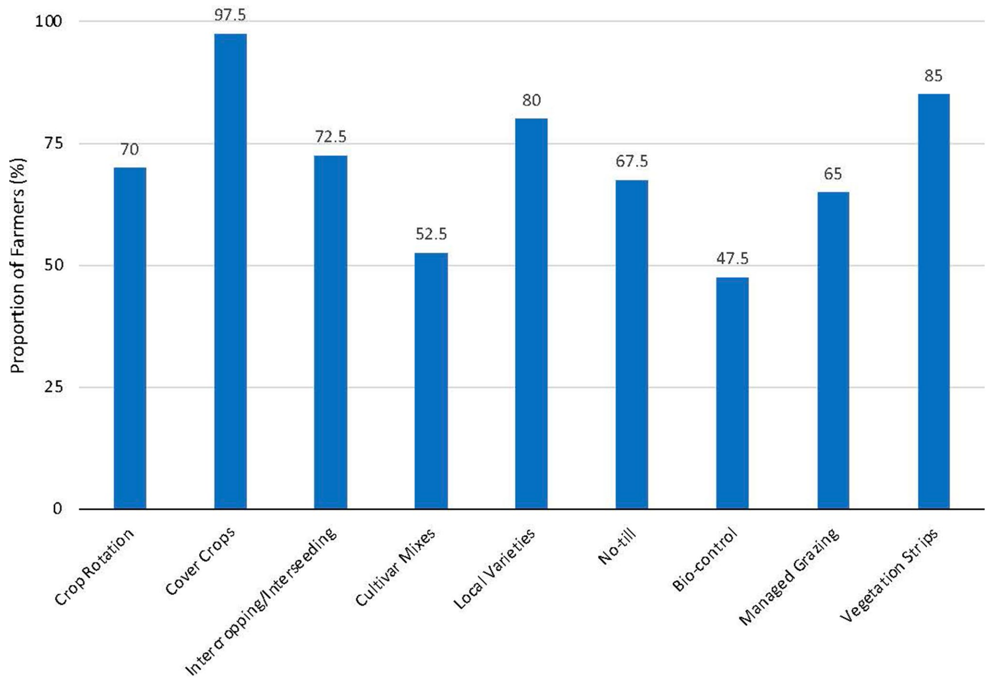


FIGURE 3
Proportion of farmers implementing pre-defined agroecological conservation practices.

beneficial insect habitat (Grashof-Bokdam and Van Langevelde, 2005; Herzog et al., 2005; Schweiger et al., 2005). This lack of association with pest management could be due to the inconsistent benefits of vegetation strips on reducing pest populations at field scale after implementation of those practices for other ecosystem services, such as erosion control and water management. Further, despite increases in beneficial insect populations when prairie strips are used (Haaland et al., 2011; Middleton et al., 2021), pest insect predation and subsequent pest pressure on crops can be neutral or inconsistent (Cox et al., 2014), further contributing to lack of farmer association of this practice with pest management benefits.

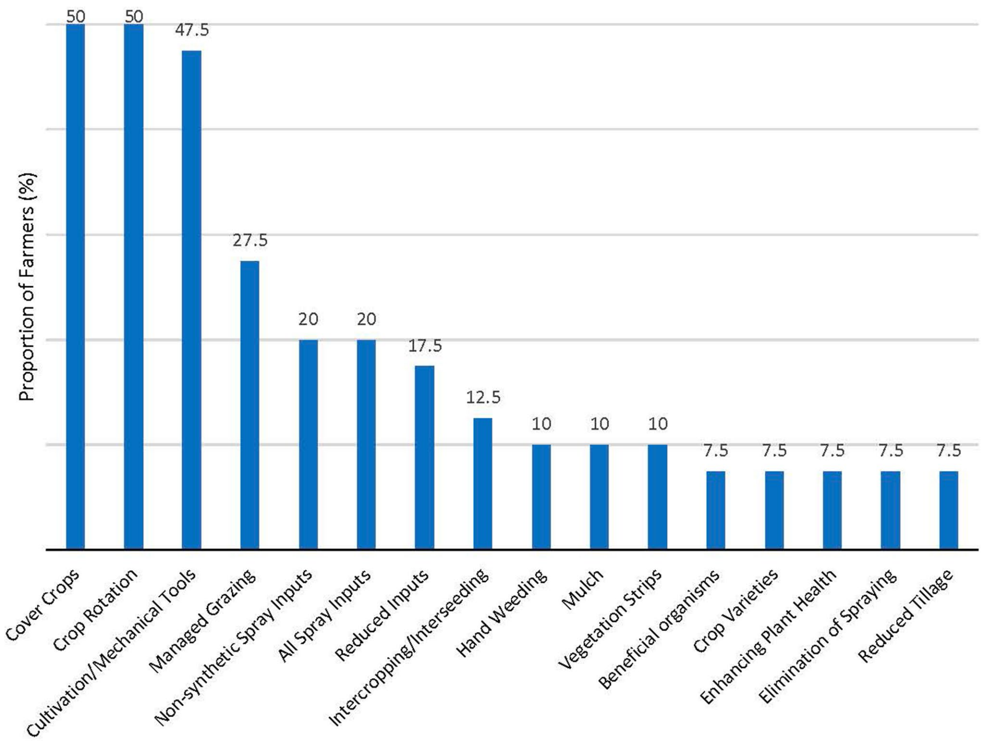


FIGURE 4
Farmer-identified crop protection practices (practices are only shown if mentioned by more than 5% of farmers).

3.4. Financial support for practices

The majority of the of the interviewees (75%) received financial support for the implementation of conservation practices from various state, federal, or private programs. Federal programs included those administered through the United States Department of Agriculture Natural Resource Conservation Service (USDA NRCS), such as the Conservation Reserve Program (CRP), the Environmental Quality Incentives Program (EQIP), and the Conservation Stewardship Program (CSP). EQIP and CSP are both intended to assist farmers in paying for integrating conservation practices on their farm. EQIP payments are intended for small, individual projects such as planting grass seed in waterways to prevent erosion, whereas CSP is intended to help pay for whole-farm projects, typically integrating multiple projects for broader aims such as erosion control, water quality or wildlife habitat enhancement. To a lesser extent, farmers cited support from the Farm Services Agency (FSA), crop insurance programs [e.g., Agriculture Risk (ARC) and Price Loss Coverage (PLC) programs]. Examples of state-based programs included funding focused on water quality protection (such as through the Wisconsin and Minnesota State Departments of Agriculture) while private funding included non-profit entities such as Ducks Unlimited.

Farmers who received financial assistance were more likely to integrate vegetation strips (including for the management of waterways and pollinator habitat) into their farm practices (Figure 5). The relationship between financial compensation and practice implementation may be related to the lack of association with other benefits that could provide economic benefits, such as improved pest control and subsequent ability to reduce inputs. A slightly higher occurrence of no-till practices and managed grazing was associated with financial assistance. The use of diverse crop rotations, intercropping, cultivar mixtures and biocontrol were more often associated with farmers not receiving financial incentive payments.

Previous studies have documented associations between financial assistance payments and the adoption of specific conservation practices. For example, the implementation of perennial covers associated with pasture, riparian buffers, and restored wetlands, which have been perceived by farmers as expensive conservation practices, have often required monetary incentives to make implementation feasible (Atwell et al., 2008). However, previous research has also shown that farmers adopt conservation practices for multiple reasons (e.g., normative obligations) other than financial incentives (Prager and Posthumus, 2010; Osmond et al., 2015; Meijboom and Stafleu, 2016) thus, the relative impact of financial assistance on facilitating practice adoption will likely be practice specific as well as due to intrinsic motivation and technical skills of farmers to adopt them (Atwell et al., 2008; Prager and Posthumus, 2010).

Different studies that have shown that farmers do not necessarily require cost-share or financial incentives to maintain commitment to certain agroecological practices that improve soil health and improve water quality, such as cover crops (Dunn et al., 2016; Roesch-McNally et al., 2017c). Thus, the design of incentive programs to promote and sustain adoption of agroecological practices should also consider broader farmer motivations leading to greater commitment to maintaining agroecological principles as part of systems-based management. Other policy supports, such as funding for improved aggregation and processing infrastructure as well as incentives for institutional procurement, could help support the financial viability

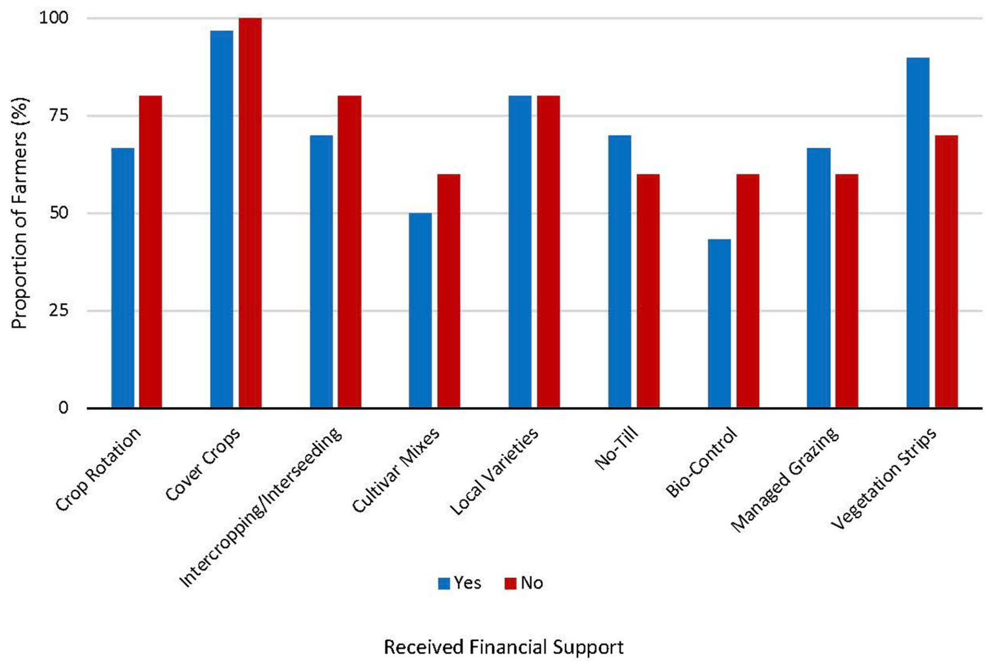


FIGURE 5
Adoption of agroecological conservation practices by farmers with and without financial support. Proportion of farmers (%) calculated by comparing the number of farmers adopting the conservation practice within each specific category with the total number of farmers overall in each category (with and without receiving financial support).

of a more diverse crop rotation, enabling the integration of agroecological processes by expanding access to more profitable market outlets for a wider variety of crop and animal-based products.

3.5. Impact on organic certification of conservation practice adoption

Approximately half of the farmers interviewed had at least some of their land managed as certified organic under the USDA National Organic Program (NOP) (Table 1). Overall, we found no association of organic certification with the number of conservation practices implemented by farmers (value of $p = 0.654$). However, differences were seen in the type of practices implemented by farmers managing at least a portion of their farm as certified organic (Figure 6). Certain conservation practices (crop rotation, cultivar mixtures, local varieties, biocontrol, managed grazing, and vegetation strips) were implemented more frequently by organic certified farms as compared to conventional farms, and certain practices less frequently used on organic farms, such as no-till practices.

Differences in the implementation of conservation practices by organic and conventional producers has been documented in previous studies. For example, nearly 40% of all organic field producers used cover crops in 2014, higher the number of conventional farmers using this practice in 2012 (7%) (Hellerstein et al., 2019). Similar trends can be observed with the practice of management intensive grazing, where 65% of organic livestock producers used rotational grazing, compared with 22% of conventional livestock producers in 2012. Further, 36% of organic farms were reported to use no-till or minimal till practices in 2019, compared to 24% of conventional farms identifying the use of these practices (USDA, 2017, 2019). Other studies have documented that organic farmers have greater environmental awareness and concern for the environment than their conventional counterparts, as documented in several studies from across the globe (Dubgaard and Sorensen, 1988; Fisher, 1989; Sullivan et al., 1996; McCann et al., 1997; Fairweather, 1999).

3.6. Adoption of multiple conservation practices

The farmers interviewed for this study typically integrated more than one conservation practice into their farming operation. The heatmap (Figure 7) generated from their responses shows that farmers using cover crops, the most frequently used conservation practice, more frequently also integrated the use of grass strips and local varieties. Further, farmers using cover crops also tended to more frequently use practices such as intercropping, crop rotation and no-till. Biocontrol and flower strips are the less frequently used overall as individual practices and were less frequently associated with the use of no-till practices and cultivar mixes. Interestingly, flower strips were not associated with the use of biocontrol practices, which may indicate that farmers associate the planting with strips more with pollinator habitat than biocontrol benefits.

The associated use of specific practices might be also related to the major motivations of farmers implementing conservation practices. Here, soil health is the leading motivation as shown in the following section. The practices targeting soil health and which were more often used also in association were cover crops, intercropping, crop rotation and no-till.

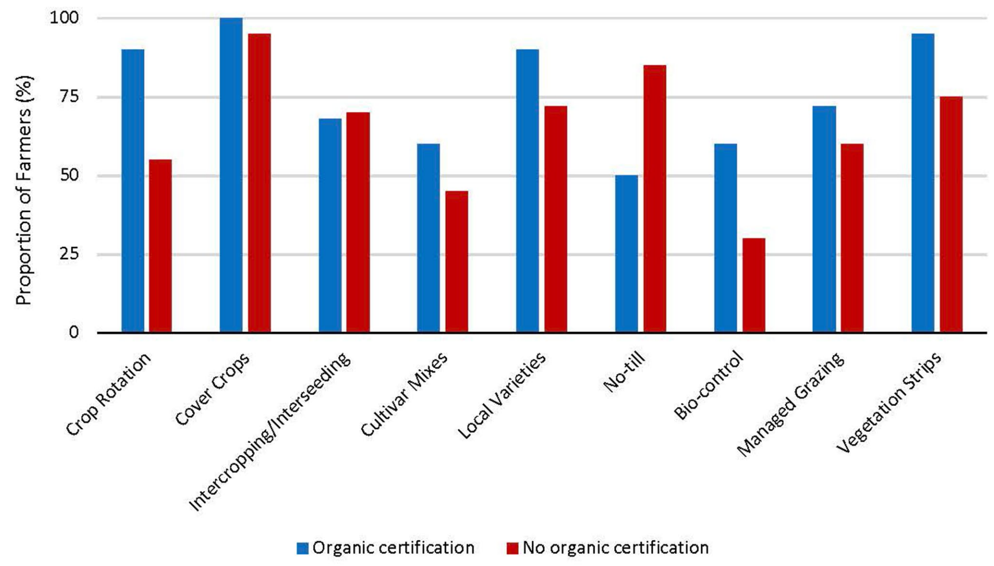


FIGURE 6
Adoption of agroecological conservation practices by farmers with and without organic certification. Proportion of farmers (%) calculated by comparing the number of farmers adopting the conservation practice within each specific category with the total number of farmers overall in each category (with and without organic certification).

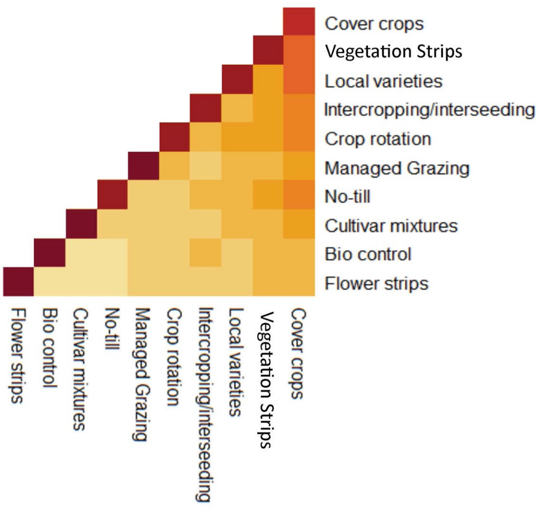


FIGURE 7
Heat map indicating combination of practices among farmers found (darker orange indicates higher frequency whereas light yellow low frequency).

3.7. Motivations to implement conservation practices

Interviewees mentioned different drivers influencing the implementation of conservation practices (Figure 8). Improving soil quality was the main motivation for farmers (55%) to implement conservation practices, often with the more specific goal of improving soil biological activity. Other soil quality enhancements sought by farmers in our study included improved soil structure and improved ability to retain nutrients. Maintaining or improving water quality and water management also ranked high with respect to farmer motivations of adoption of conservation practices, with erosion, water retention and water quality appearing in 60% of the answers of interviewees.

Other studies have similarly found that soil quality and health-related benefits were motivators for the adoption of conservation practices, including erosion reduction from cover crops, filter strips, grassed waterways, hedgerows, rotational grazing, and no-till (Brodt et al., 2009; Reimer et al., 2012; Brummel and Nelson, 2014; Reimer and Prokopy, 2014; Xie, 2014; Roesch-McNally et al., 2017a,b,c), as well as soil improvements associated with the implementation of perennials, organic practice in general, cover crops, no-till, and rotational grazing (Brummel and Nelson, 2014; Reimer and Prokopy, 2014; Adebiyi et al., 2016; Bossange et al., 2016; Ulrich-Schad et al., 2017). The types of practices implemented most frequently by the farmers in our study align with the motivation of improved soil health. Cover crops are widely viewed by technical soil and water conservation advisors to be an effective means for reducing soil erosion and nutrient loss and increasing soil health (Arbuckle and Roesch-McNally, 2015). Similarly, vegetation strips are a common practice to implement in waterways and reduce erosion. As several of the farmer groups from which our interview sample was recruited have an emphasis on water quality (e.g., Practical Farmers of Iowa and Wisconsin's Farmer-Led Watershed groups), our interviewees likely had substantial opportunities to become familiar with research and best management practices which link conservations strategies to erosion management.

Profitability was identified as a second important motivator for the adoption of conservation practices. Within this context of a motivator, profitability can be viewed from two perspectives. First, farmers recognized the potential economic savings that could result from the implementation of conservation farming practices, including the reduced need for inputs to manage weeds, insects, and diseases, or the reduced fuel costs due to fewer field operations (e.g., with no-till

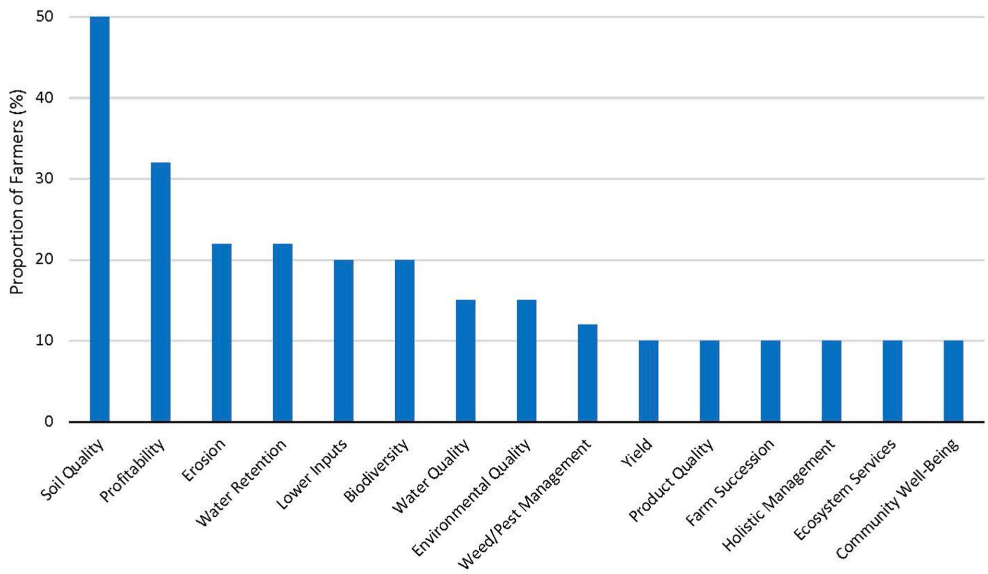


FIGURE 8
Main motivations for implementation of agroecological conservation farming practices (motivation themes are only shown if mentioned by at least 10% of farmers).

management or managed grazing). Other studies have found that reduced input costs, including fuel, labor, and nutrient additions, were a motivation to practice adoption (Reimer et al., 2012; Stuart et al., 2014). The second aspect of profitability which motivated farmers was related to increased yields or market premiums that were realized when these practices were adopted.

Several studies have showed that farmers' perceptions of the importance of soil health as a broader asset to their farm, as well as the specific economic benefits of soil health practices, both play important roles in conservation practice adoption (Singer et al., 2007; Bergtold et al., 2012; Reimer and Prokopy, 2014; Wang et al., 2019). More specifically, previous literature has documented that farmers' emphases on improving soil health and the related soil health attributes of the new practice tend to positively influence adoption decisions, while farmers who need more monetary incentives to adopt such practices are less likely to adopt (Adesina and Baidu-Forson, 1995; Ryan et al., 2003; Singer et al., 2007; Bergtold et al., 2012; Reimer and Prokopy, 2014; Wang et al., 2019). The motivation of soil health may be related to the farmers' assumptions that these improvements will increase yields while reducing the need for chemical inputs, which will improve their profitability in the longer term (Plastina et al., 2020). These studies, complemented by the results of our interviews, highlight the importance of not only understanding the economic scenarios related to conservation practice outcomes and supports, but also helping farmers better understand the broader value of agroecological practices to their operations, particularly those related to the improved function of their farms in the longer term.

To a lesser extent, biodiversity and mitigation of environmental stresses (e.g., water stress) were stated as main drivers by 20% and 12.5% of farmers, respectively. Similarly, social motivations related to the adoption of conservation practices were less cited, although farmers did state a desire to adopt practices that promoted their ability to be responsible stewards the land, particularly as related to maintaining and restoring the land for future generations. In a recent study of organic grain farmers in Iowa, a similar lower prioritization was placed on broader social benefits, where civic-mindedness goal orientation was rated lower than the goals of profitability and natural resource stewardship (Han et al., 2021).

Livestock grazing can also motivate the adoption of conservation practices. Farmers with livestock perceived higher levels of compatibility between their systems and cover crops (Arbuckle and Roesch-McNally, 2015). These results suggest that integrating livestock in cropping systems could further facilitate conservation practice implementation while providing additional landscape-level benefits (e.g., weed/insect suppression or extreme weather mitigation) that come with a more diversified agricultural system (Lin, 2011; Davis et al., 2012; Kremen and Miles, 2012). A significant number of farmers interviewed mentioned currently practicing grazing livestock on crop fields as well as the desire to do it in the future. Integration of livestock into grain cropping systems is of increasing interest to farmers seeking more advanced goals related to soil health on their farms, as it is a key element listed in the NRCS five soil health principles (USDA NRCS, 2022).

3.8. Barriers to implementation

Several barriers were identified to farmer adoption of conservation practices. Costs (e.g., the purchase of fencing for management intensive grazing, seed, or additional equipment) (32.5%) and the lack of knowledge (e.g., the need for specific guidance regarding best management practices for successful implementation of practices) (27.5%) were the main barriers stated by farmers (Figure 9). Beyond lack of knowledge, access to physical resources (e.g., specialized equipment; markets for more diversified crop rotation) was considered by 22.5% of the farmer as a limit to the implementation. Additionally, farmers identified financial limitations, as well as limitations with time and labor, as barriers to the implementation of conservation practice adoption.

Time and labor have been documented as barriers to conservation practice adoption (Reimer et al., 2012). Not only is the overall additional labor demand related to implementation of practices a concern, but those labor needs coming at critical times in farm management. For example, lack of timely cover crop termination and residue incorporation due to delayed operations can lead to production risks if farmers cannot manage the cover crop at an earlier growth stage appropriate for effective nutrient management and planting (Christianson et al., 2014).

Lack of knowledge, uncertainty of production outcomes, and greater perceived risk have also been cited as barriers to adoption of conservation practices. A survey related to cover crop implementation in the midwestern USA found that if technical assistance were more widely available, more farmers would attempt to use of cover crops (Arbuckle and Roesch-McNally, 2015). This same study showed that farmers who implemented cover crops were more likely to have support from conservation agencies and watershed groups, demonstrating the positive impact of access to knowledge. Adoption of other conservation practices have shown similar trends, such as the implementation of prairie strips for biodiversity (Luther et al., 2022). Further, improved infrastructure and resources to support conservation practice adoption, including the need for greater availability of seed, equipment, and expertise, remains lacking (Arbuckle and Roesch-McNally, 2015).

A further barrier is that changes in supply chains more broadly are also necessary to expand the implementation of agroecological practices, particularly in the geographic region from which our interview pool is drawn, which is dominated by the production of corn and soybean for animal feed. The narrow rotation of long-season crops limits the possibility of integrating alternative practices, such as cover crops and grazing, into the system (Peterson et al., 2019). Previous studies have documented those farmers who had more diverse operations, including the integration of livestock or additional crops, more successfully integrated cover crops into their farming operations (Stuart and Gillon, 2013). However, despite proven agroecological benefits as well as benefits to yields (Volsi et al., 2022), adoption of diverse rotations is hindered by lack of readily accessible and profitable regional markets. Alternative marketing strategies such as cooperative marketing, direct marketing, and institutional procurement programs, partnered with increased infrastructure capacity to shortened supply chains, could facilitate expanded implementation of diverse rotations and, in turn, facilitate agroecological practice adoption. The structural barriers existing beyond the farm can drive farm management decisions, limiting innovation and willingness to attempt alternative farm strategies (Bartels et al., 2013).

3.9. Planned future implementation of practices

Farmers were asked about additional conservation practices planned for the future. Almost all farmers (92.5%) were considering the implementation of at least one new practice. Increasing the use of cover crops, as well as planting more trees, were frequently mentioned practice changes, with about 20% of farmers seeking these goals (Figure 10). Expanded or new implementation of no-till practices was mentioned as by 20% of the farmers interviewed, while 17.5% planned to improve their management intensive grazing systems and add practices to improve biodiversity. This goal to increase biodiversity was often expressed as a broader goal of environmental protection, but also as a desire to support pollinators and beneficial insects.

3.10. Study limitation

Some limitations of the study can be mentioned here. There was no representative sampling of farms per type of farming, farm size or other factor that was carried out. But the goal was an exploratory study to get first insights into the use of conservation practices of

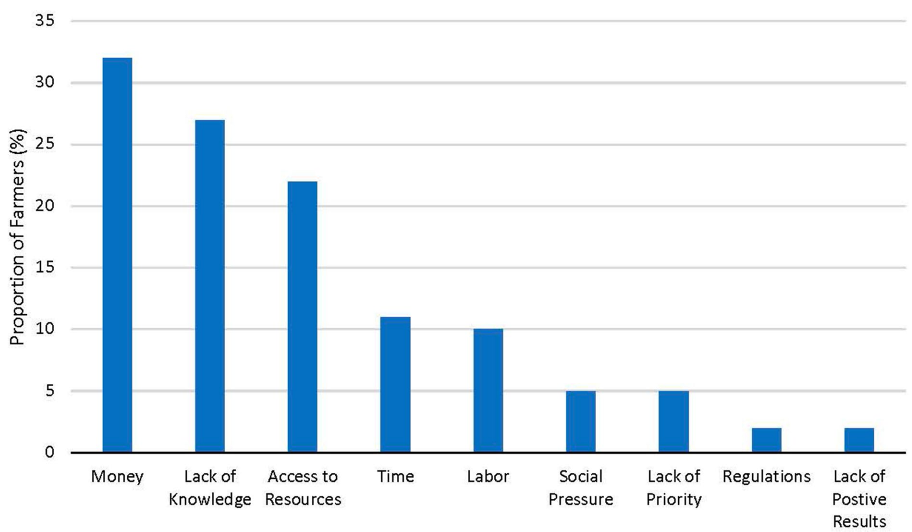


FIGURE 9
Barriers to implementation of agroecological conservation farming practices (barrier themes are only shown if mentioned by at least 5% of farmers).

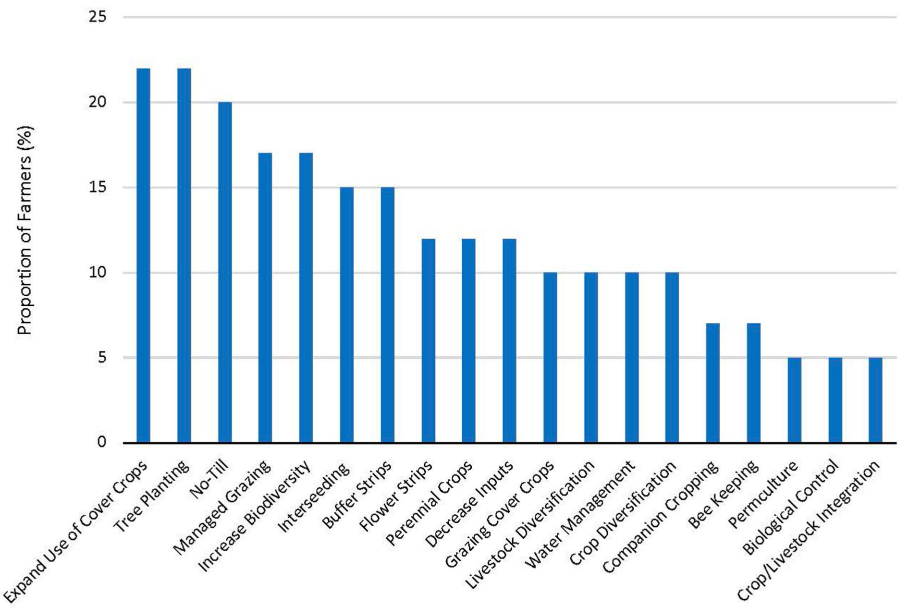


FIGURE 10
Future plans for implementation of agroecological conservation practices identified by farmers (practices are only shown if mentioned by at least 5% of farmers).

farmers, farmers' motivations to use them and barriers for implementation. A second one is that we could only survey which practices farmers use on the farm, but not explicitly on each field or plot of their farm. For this a much larger study would be needed in investigating the use of conservation practices per field, but this was not feasible. In such a future study, field investigations would also be necessary and relating the use of practices to, e.g., soil type, crops grown, rotation, location on the farm per field. Moreover, we could see with some data analysis not presented here that there are some tendencies in the use of some practices regarding farm size. More in-depth analyses, with additional farm data, and investigating as well differences regarding farming types or for which crops the practices are used could provide further insights into the adoption of conservation practices.

4. Conclusion

This study broadens our understanding of the adoption patterns of different conservation farming practices implemented by farmers demonstrating an existing interest in their use. Our results show that many of the farmers interviewed used not just one conservation practice, but typically use multiple conservation practices. This study showed that conservation practices with the highest adoption tended to be the practices most often co-adopted. And for this soil health seems to be an important driver and motivation for farmers to adopt them. However, we also found certain practices that were less likely to be used in combination.

Our data also demonstrated that the conservation practices with high levels of adoption (e.g., cover crops) had substantial support with respect to technical assistance and financial assistance. However, our study also highlights practices that would profit from more investment in the development of successful implementation strategies, supported by providing specific additional financial incentives for them, such as the use of flowering strips and enlarged use of biocontrol. Understanding how to design complementarity between more frequent and lesser used practices (e.g., managing pastures to enhance beneficial insect habitat, using diverse cover crop mixes with flowering species) could derive additional agroecological benefits from practice implementation while mitigating risks and financial burdens to the farmer. Additionally, understanding complementarities, as well as differences in barriers and motivation, can help design more holistic financial incentive schemes to promote practices that are riskier or knowledge intensive to implement, yet may provide substantial agroecosystem benefits.

The impact of certification strategies on adoption of some practices also emerged from our study. As public and private programs, including those related to "regenerative" or "climate smart" agriculture, continue to develop, the inclusion of certain conservation practices within these certification schemes could be a positive driver with respect to further implementation.

The motivations and barriers faced by the farmers in this study, who already had made steps to implement conservation practices on their farms, were consistent with those documented in previous studies. A persistent need exists for more knowledge and resources not only the technical details related to the execution of practices, but also the short and long-term soil health benefits and economic impacts. The dual motivations of broader goals of soil health improvement and profitability must be considered in designing education and incentive programs to motivate new and sustained adoption of practices. The findings outlined in this study also highlight the role of farmer networks, particularly those with a conservation focus, in reducing barriers through creating learning communities to not only accelerate knowledge generation and sharing, but to alleviate the social barriers that inhibit farmer adoption of conservation practices.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AW and ES: conceptualization. AW, ES, and MR: research design. CS, JB, NB, NC, CC, and MB: data collection. NB, JB, NC, CC, CS, AW, and ES: data analysis and interpretation and writing manuscript. AS, CS, JB, and ES: editing manuscript. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the University of Wisconsin-Madison Organic Collaborative and the Agroecology program at ISARA.

Acknowledgments

We are highly grateful to the farmers that were willing to share their time and knowledge with us for data collection.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Adesina, A., and Baidu-Forson, J. (1995). Farmers' perceptions and adoption of new agricultural technology: evidence from analysis in Burkina Faso and Guinea, West Africa. *Agric. Econ.* 13, 1–9. doi: 10.1016/0169-5150(95)01142-8

Adebiyi J, Olabisi L. S., Snapp S. (2016). Understanding perennial wheat adoption as a transformative technology: evidence from the literature and farmers. *J. Renew. Agric. Food Syst.* 31, 101–110.

Arbuckle, J. G., and Roesch-McNally, G. (2015). Cover crop adoption in Iowa: the role of perceived practice characteristics. *J. Soil Water Conserv.* 70, 418–429. doi: 10.2489/jswc.70.6.418

Atwell, R. C., Schulte, L. A., and Westphal, L. M. (2008). Linking resilience theory and diffusion of innovations theory to understand the potential for perennials in the U.S. Corn Belt. Ecology and society 14(1): 30. Available at: http://www.ecologyandsociety.org/vol14/iss1/art 30/

Banga, S. S., and Kang, M. S. (2014). Developing climate-resilient crops. *J. Crop Improv.* 28, 57–87. doi: 10.1080/15427528.2014.865410

Bartels, W. L., Furman, C. A., Diehl, D. C., Royce, F. S., Dourte, D. R., Ortiz, B. V., et al. (2013). Warming up to climate change: a participatory approach to engaging with stakeholders in the southeast US. *Reg. Environ. Chang.* 13, 45–S55. doi: 10.1007/s10113-012-0371-9

Bergtold, J. S., Duffy, P. A., Hite, D., and Raper, R. L. (2012). Demographic and management factors affecting the adoption and perceived yield benefit of winter cover crops in the southeast. *J. Agric. Appl. Econ.* 44, 99–116. doi: 10.1017/S1074070800000195

Bezner Kerr, R., Madsen, S., Stüber, M., Liebert, J., Enloe, S., Borghino, N., et al. (2021). Can agroecology improve food security and nutrition? A review. *Glob. Food Sec.* 29:100540. doi: 10.1016/j.gfs.2021.100540

Boeraeve, F., Dendoncker, N., Cornélis, J. -T., Degrune, F., and Dufrene, M. (2020). Contributution of agroecological farming systems to the delivery of ecosystems services. *J. Environ. Manage.* 260:109576. doi: 10.1016/j.jenvman.2019.109576

Bossange, A. V., Knudson, K. M., Shrestha, A., Harben, R., and Mitchell, J. P. (2016). The potential for conservation tillage adoption in the San Joaquin Valley, California: a qualitative study of farmer perspectives and opportunities for extension. *PLoS ONE* 11:e0167612. doi: 10.1371/journal.pone.0167612

Brodt, S., Klonsky, K., Jackson, L., Stephen, B. Brush and Sean Smukle. (2009). Factors affecting adoption of hedgerows and other biodiversity-enhancing features on farms in California, USA. *Agroforest Syst.* 76, 195–206. doi: 10.1007/s10457-008-9168-8

Brummel, R. F., and Nelson, K. C. (2014). Does multifunctionality matter to US farmers? Farmer motivations and conceptions of multifunctionality in dairy systems. *J. Environ. Manage.* 146, 451–462. doi: 10.1016/j.jenvman.2014.07.034

Canales, E., Bergtold, J. S., and Williams, J. R. (2020). Conservation practice complementarity and timing of on-farm adoption. *Agric. Econ.* 51, 777–792. doi: 10.1111/agec.12591

Christianson, R., Christianson, L., Wong, C., Helmers, M., McIssac, G., and Mulla, D. (2018). Beyond the nutrient strategies: common ground to accelerate agricultural water quality improvement in the upper Midwest. *J. Environ. Manag.* 206, 1072–1080. doi: 10.1016/j.jenvman.2017.11.051

Christianson, L., Knoot, T., Larsen, D., Tyndall, J., and Helmers, M. (2014). Adoption of potential nitrate mitigation practices: an ecosystem approach. *Int. J. Agric. Sustain.* 12, 407–424. doi: 10.1080/14735903.2013.835604

Cox, R., O'Neal, M., Hessel, R., Schulte, L. A., and Helmers, M. (2014). The impact of prairie strips on Aphidophagous predator abundance and soybean aphid predation in agricultural catchments. *Environ. Entomol.* 43, 1185–1197. doi: 10.1603/EN13129

Davis, T. S., Boundy-Mills, K., and Landolt, P. J. (2012). Volatile emissions from an epiphytic fungus are semiochemicals for eusocial wasps. *Microb. Ecol.* 64, 1059–1064. doi: 10.1007/s00248-012-0074-2

Debray, V., Wezel, A., Lambert-Derkimba, A., Roesch, K., Leiblin, G., and Francis, C. A. (2019). Agroecological practices for climate change adaptation in semiarid and subhumid Africa. *Agroecol. Sustain. Food Syst.* 43, 429–456.

Dubgaard, A., and Sorensen, S. N. (1988). *Organic and bio-dynamic farming in Denmark: a statistical survey*. Rapport, Statens-Jordbrugsokonomiske Institut, Denmark, *43*, 33 pp.

Dunn, M., Ulrich-Schad, J. D., Prokopy, L. S., Myers, R. L., Watts, C. R., and Scanlon, K. (2016). Perceptions and use of cover crops among early adopters: findings from a national survey. *J. Soils Water Conserv.* 71, 29–40. doi: 10.2489/jswc.71.1.29

Fairweather, J. R. (1999). Understanding how farmers choose between organic and conventional production: results from New Zealand and policy implications. *Agric. Hum. Values.* 16, 51–63. doi: 10.1023/A:1007522819471

Findlater, K. M., Kandlikar, M., and Satterfield, T. (2019). Misunderstanding conservation agriculture: challenges in promoting, monitoring and evaluating sustainable farming. *Environ. Sci. Policy* 100, 47–54. doi: 10.1016/j.envsci.2019.05.027

Fisher, P. (1989). *Barriers to the adoption of organic farming in Canterbury* Centre for Resource Management, Lincoln College.

Foltz, J., and Lang, G. (2005). The adoption and impact of management intensive rotational grazing (MIRG) on Connecticut dairy farms. *Renew. Agric. Food Syst.* 20, 261–266. doi: 10.1079/RAF2005127

Gong, S., Bergtold, J. S., and Yeager, E. (2021). Assessing the joint adoption and complementarity between in-field conservation practices of Kansas farmers. *Agri. Food Econ.* 9, 1–24. doi: 10.1186/s40100-021-00201-8

Grashof-Bokdam, C. J., and Van Langevelde, F. (2005). Green veining: landscape determinants of biodiversity in European agricultural landscapes. *Landsc. Ecol.* 20, 417–439. doi: 10.1007/s10980-004-5646-1

Haaland, C., Naisbit, R. E., and Bersier, L. F. (2011). Sown wildflower strips for insect conservation: a review. *Insect Conserv. Diver.* 4, 60–80. doi: 10.1111/j.1752-4598.2010.00098.x

Han, G., Arbuckle, J. G., and Grudens-Schuck, N. (2021). Motivations, goals, and benefits associated with organic grain farming by producers in Iowa, US. *Agric. Syst.* 191:103175. doi: 10.1016/j.agsy.2021.103175

Hatt, S., Boeraeve, F., Artru, S., Dufrene, M., and Francis, F. (2018). Spatial diversification of agroecosystems to enhance biological control and other regulating services: an agroecological perspective. *Sci. Total Environ.* 621, 600–611. doi: 10.1016/j.scitotenv.2017.11.296

Hellerstein, D., Viorio, D., Ribaudo, M., Aillery, M., Bigelow, D., Bowman, M., et al. (2019). Agricultural resources and environmental indicators, 2019. *Econ. Inform. Bull.* EIB-208:142.

Herzog, F., Dreier, S., Hofer, G., Marfurt, C., Schupbach, B., Spiess, M., et al. (2005). Effect of ecological compensation areas on floristic and breeding bird diversity in Swiss agricultural landscapes. *Agric. Ecosyst. Environ.* 108, 189–204. doi: 10.1016/j.agee.2005.02.003

Jat, R. A., Sahrawat, K., Kassam, A., and Friedrich, T. (2014). *Conservation agriculture for sustainable and resilient agriculture: global status, prospects and challenges*. Editors: R.A. Jat, K.L. Sahrawat and A.H. Kassam Wallingford, Oxfordshire, UK: CABI International.

Krause, M. A. (2017). Optimal adoption strategies for no-till technology. *Am. J. Agric. Econ.* 75:1296.

Kremen, C., and Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecol. Soc.* 17:40.

Kuhn, K. (2018). Benefits of conservation planning to farmers, landowners, and society. Webinar, Ames, IA: Iowa. Available at: https://vimeo.com/user42671352/review/290760563/4af;a07b69.

Lee, S., and McCann, L. (2019). Adoption of cover crops by US soybean producers. *J. Agric. Appl. Econ.* 52, 527–544.

Liebert, J., Benner, R., Bezner Kerr, R., Björkman, T., Teigen De Master, K., Gennet, S., et al. (2022). Farm size affects the use of agroecological practices on organic farms in the United States. *Nat. Plants* 8, 897–905. doi: 10.1038/s41477-022-01191-1

Lin, B. B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. *Bio Sci.* 61, 183–193.

Luther, Z. R., Swinton, S. M., and Van Deynze, B. (2022). Potential supply of Midwest cropland for conversion to in-field prairie strips. *Land Econ.* 98, 274–291. doi: 10.3368/le.98.2.082020-0129R1

McCann, E., Sullivan, S., Erickson, D., and DeYoung, R. (1997). Environmental awareness, economic orientation, and farming practices: a comparison of organic and conventional farmers. *Environ. Manag.* 21, 747–758. doi: 10.1007/s002679900064

Meijboom, F. L. B., and Stafleu, F. R. (2016). Farming ethics in practice: from freedom to professional moral autonomy for farmers. *Agric. Hum. Values.* 33, 403–414.

Middleton, E. G., Mac Rae, I. V., and Philips, C. R. (2021). Floral plantings in large-scale commercial agroecosystems support both pollinators and arthropod predators. *Insects* 12:91. doi: 10.3390/insects12020091

Moore, V. M., Mitchell, P. D., Silva, E. M., and Barham, B. L. (2016). Cover crop adoption and intensity on Wisconsin's organic vegetable farms. *Agroecol. Sustain. Food Syst.* 40, 693–713. doi: 10.1080/21683565.2016.1181694

Osmond, D. L., Hoag, D. L., Luloff, A. E., Meals, D. W., and Neas, K. (2015). Farmers' use of nutrient management: lessons from watershed case studies. *J. Environ. Qual.* 44, 382–390. doi: 10.2134/jeq2014.02.0091

Paracchini, M., Justes, E., Wezel, A., Zingari, P. C., Kahane, R., Madsen, S., et al. (2020). *Agroecological practices supporting food production and reducing food insecurity in developing countries*, Publications Office of the European Union, Luxembourg

Peterson, A. T., Berti, M. T., and Samarappuli, D. (2019). Intersowing cover crops into standing Soybean in the US upper midwest. *Agronomy.* 9:264. doi: 10.3390/agronomy9050264

Plastina, A., Liu, F., Miguez, F., and Carlson, S. (2020). Cover crops use in Midwestern US agriculture: perceived benefits and net returns. *Renew Agric Food Syst.* 35, 38–48. doi: 10.1017/S1742170518000194

Prager, K., and Posthumus, H. (2010). "Socio-economic factors influencing farmers' adoption of soil conservation practices in Europe" in *Human dimensions soil and water conservation*. ed. T. L. Napier (United Kingdom: Nova Science Publications), 1, 388–321.

Reimer, A. P., and Prokopy, L. S. (2014). Farmer participation in US farm bill conservation programs. *Environ. Manag.* 53, 318–332. doi: 10.1007/s00267-013-0184-8

Reimer, A., Thompson, A., and Prokopy, L. (2012). The multi-dimensional nature of environmental attitudes among farmers in Indiana: implications for conservation adoption. *Agric. Hum. Values* 29, 29–40. doi: 10.1007/s10460-011-9308-z

Roesch-McNally, G. E., Arbuckle, J. G., and Tyndall, J. C. (2017a). What would farmers do? Adaptation intentions under a corn belt climate change scenario. *Agric. Hum. Values* 34, 333–346. doi: 10.1007/s10460-016-9719-y

Roesch-McNally, G. E., Arbuckle, J. G., and Tyndall, J. C. (2017b). Soil as social-ecological feedback: examining the ethic of soil stewardship among Corn Belt farmers. *Rural. Sociol.* 83, 145–173. doi: 10.1111/ruso.12167

Roesch-McNally, G. E., Basch, A., Arbuckle, J. G., Tyndall, J. C., Miguez, F., Bowman, T., et al. (2017c). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renew. Agric. Food Syst.* 33, 322–333. doi: 10.1017/S1742170517000096

Ryan, R. L., Erickson, D. L., and De Young, R. (2003). Farmers' motivations for adopting conservation practices along riparian zones in a mid-western agricultural watershed. *J. Environ. Plan. Manag.* 46, 19–37. doi: 10.1080/713676702

Sawadgo, W., and Pastina, A. (2022). The invisible elephant: disadoption of conservation practices in the United States. Choices. Quarter 1. Available at: https://www.choicesmagazine.org/choices-magazine/submitted-articles/the-invisible-elephant-disadoption-of-conservation-practices-in-the-united-states

Schweiger, O., Maelfait, J. P., Van Wingerden, W., Hendricks, F., Billeter, R., Speelmans, M., et al. (2005). "Quantifying the impact of environmental factors on arthropod communities in agricultural landscapes across organizational levels and spatial scales" in *Landscape ecology for sustainable environment and culture*, chapter 14. eds. F. Bojie and B. Jones (Dordrecht Heidelberg, NY, London: Springer Publishing).

Singer, J. W., Nusser, S. M., and Alf, C. J. (2007). Are cover crops being used in the US corn belt? *J. Soil Water Conserv.* 62, 353–358.

Stuart, D., and Gillon, S. (2013). Scaling up to address new challenges to conservation on US farmland. *Land Use Policy* 31, 223–236. doi: 10.1016/j.landusepol.2012.07.003

Stuart, D., Schewe, R. L., and McDermott, M. (2014). Reducing nitrogen fertilizer application as a climate change mitigation strategy: understanding farmer decision-making and potential barriers to change in the US. *Land Use Policy* 36, 210–218. doi: 10.1016/j.landusepol.2013.08.011

Sullivan, S., McCann, E., de Young, R., and Erickson, D. (1996). Farmers' attitudes about farming and the environment: a survey of conventional and organic farmers. *J. Agric. Environ. Ethics* 9, 123–143. doi: 10.1007/BF03055298

Ulrich-Schad, J. D., Brock, C., and Prokopy, L. S. (2017). A comparison of awareness, attitudes, and usage of water quality conservation practices between Amish and non-Amish farmers. *Soc. Nat. Resour.* 30, 1476–1490. doi: 10.1080/08941920.2017.1364457

USDA. (2017). Census of agriculture. Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US

USDA. (2019). 2019 organic survey. Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Organics/ORGANICS.pdf

USDA NRCS. (2013). *National and state resource concerns and planning criteria*. Washington, DC: USDA NRCS.

USDA NRCS. (2022). Soil health. Available at: https://www.nrcs.usda.gov/wps/portal/nrcs/main/nd/soils/health/

Volsi, B., Higashi, G. E., Bordin, I., and Santos Telles, T. (2022). The diversification of species in crop rotation increases the profitability of grain production systems. *Sicentific Rep.* 12:19849. doi: 10.1038/s41598-022-23718-4

Wade, T., Claassen, R., and Wallander, S. (2015). Conservation-practice adoption rates vary widely by crop and region. USDA Economic Research Service Economic Information Bulletin Number 147. Available at: https://www.ers.usda.gov/webdocs/publications/44027/56332_eib147.pdf

Wade, T., and Classen, R. (2017). Modeling no-till adoption by corn and soybean producers: insights into sustained adoption. *J. Agric. Appl. Econ.* 49, 186–210. doi: 10.1017/aae.2016.48

Wang, T., Jim, H., Kasu, B. B., Jacquet, J., and Kumar, S. (2019). Soil conservation practice adoption in the northern Great Plains: economic versus Ssewardship motivations. *J. Agric. Resour. Econ.* 44, 404–421. Publisher: Unknown. doi: 10.22004/ag.econ.287989

Wang, T., Jin, H. L., Kreuter, U., Feng, H. L., Hennsesy, D. A., Teague, R., et al. (2020). Challenges for rotational grazing practice: views from non-adopters across the Great Plains, USA. *J. Environ. Manag.* 256:109941. doi: 10.1016/j.jenvman.2019.109941

Wezel, A., Casagrande, M., Celette, F., Vian, J. F., Ferrer, A., and Peigné, J. (2014). Agroecological practices for sustainable agriculture. A review. *Agron. Sustain. Dev.* 34, 1–20. doi: 10.1007/s13593-013-0180-7

Wezel, A., and Silva, E. (2017). "Agroecology and agroecological cropping practices" in *Agroecological practices for sustainable agriculture: Principles, applications, and making the transition*. ed. A. Wezel (New Jersey, USA: World Scientific), 19–51.

Winsten, J. R., Richardson, A., Kerchner, C. D., Lichau, A., and Hyman, J. M. (2020). Barriers to the adoption of management-intensive grazing among dairy farmers in the northeastern United States. *Renew. Agri. Food Syst.* 26, 104–113.

Xie, Y. (2014). *Watershed modeling, farm tenancy and adoption of conservation measures to facilitate water quality trading in the upper Scioto watershed, Ohio*. Columbus, OH: The Ohio State University.

Zulauf, C., and Brown, B. (2019). *Cover crops, 2017 US census of agriculture, farmdoc daily*. University of Illinois at Urbana-Champaign, Department of Agricultural and Consumer Economics, 9, July.

Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 15 November 2023
DOI 10.3389/fsufs.2023.1038286

OPEN ACCESS

EDITED BY
Aida Turrini,
Independent Researcher, Scansano, Italy

REVIEWED BY
Ryuma Shineha,
Osaka University, Japan
Moona Rahikainen,
University of Turku, Finland

*CORRESPONDENCE
Kathleen L. Hefferon
✉ klh22@cornell.edu

RECEIVED 06 September 2022
ACCEPTED 13 October 2023
PUBLISHED 15 November 2023

CITATION
Hefferon KL, De Steur H, Perez-Cueto FJA and Herring R (2023) Alternative protein innovations and challenges for industry and consumer: an initial overview.
Front. Sustain. Food Syst. 7:1038286.
doi: 10.3389/fsufs.2023.1038286

Alternative protein innovations and challenges for industry and consumer: an initial overview

Kathleen L. Hefferon[1]*, Hans De Steur[2], Federico J. A. Perez-Cueto[3] and Ronald Herring[4]

[1]Department of Cell Biology and Genetics, Cornell University, Ithaca, NY, United States, [2]Department of Agricultural Economics, Ghent University, Ghent, Belgium, [3]Department of Food, Nutrition and Culinary Science, Umeå University, Umeå, Sweden, [4]Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY, United States

Over one fourth of today's greenhouse gas emissions are the result of agriculture, with the production of meat representing a large portion of this carbon footprint. As the wealth of low- and middle-income countries continues to increase, the demand for animal-sourced protein, such as dairy and meat products, will escalate. At this point in time, livestock feed alone utilizes almost 40% of the world's cropland. The rapidly increasing world population, coupled with a need for environmental sustainability, has renewed our attention on animal-protein substitutes. Apprehensions over climate change have aided an acceleration in the research and development of alternative proteins, which may replace some animal-sourced protein over time. The alternative dairy and meat industry is developing at a yearly rate of 15.8% and is predicted to reach 1.2 trillion $USD by 2030. This emerging market incorporates new technologies in plant-made protein production, manufacturing of animal proteins by fermentation using microbial bioreactors, and accelerated production of cultivated (also known as cell-based) meat. These new technologies should change the global market drammatically. This article describes the history of the alternative protein industry and its' current status, then offers predictions of future pathways for this rapidly accelerating market. More speculatively, it discusses factors that lead to shifts in consumer behavior that trend toward the adoption of new technologies.

KEYWORDS

protein, sustainability, animal welfare, plant-based food, alternative meat, consumer, review

Introduction

As environmental sustainability becomes more imperative, the utility of animal-sourced food products has undergone extensive evaluation (Poore and Nemecek, 2018; Aschemann-Witzel et al., 2021). Livestock feed itself utilizes up to 40% of global cropland, and the need for meat products has grown alongside the increase in income across low- and middle-income countries (Sexton et al., 2019). Increased demand for arable land that can be used to produce animal protein is a significant cause of pollution, biodiversity loss and eutrophication through the excessive application of fertilizers. Simultaneously, more than 800 million people suffer from undernutrition and another two billion experience micronutrient malnutrition (Perignon and Darmon, 2022; World Health Organization, 2022). A doubling of food is needed to improve the nutritional status of the world's population; continuation of conventional patterns of agricultural production is estimated to create lower overall environmental sustainability, and accumulated in a sharp increase of greenhouse gas emissions of 80% (Aimutis, 2022).

Besides issues associated with sustainability, the over-consumption of meat is linked to multiple health issues including heart and cardiovascular disease and colorectal cancer (Micha et al., 2010; Wolk, 2017; González et al., 2020). Food-borne illnesses such as *Salmonella*, *E. coli* and *Campylobacter* are also associated with meat consumption; excessive use of antibiotics in livestock carries risks for human health as well (Fegan and Jenson, 2018; Lee et al., 2021).

Research into and development of animal protein replacements has resulted in an acceleration of innovation (FAO, 2022). The alternative dairy and meat industries are presently growing at a rate of 15.8%, with amplified appeal to mainstream consumers outside of the existing 'niche' markets (Specht, 2022). Meat alternatives produced presently have appealed particularly to the rapidly-growing sector of "flexitarian" consumers (Smart Protein, 2021).

For over 10 years, demand for alternative protein products from various sources has altered the marketplace (Lima et al., 2022). Alternative proteins can imitate the flavor, appearance and mouthfeel and even certain nutritional profiles of many animal products, while significantly reducing greenhouse gas emissions, land degradation and loss of diversity in wild places (Sexton et al., 2019). Finally, alternative protein can directly tackle animal welfare and ethical issues associated with animal meat production (Eckl et al., 2021). Substitutes for animal-sourced food protein respond to inter-connected concerns of sustainability, nutrition and ethical concerns toward the use of animals (Chai et al., 2019). Indeed, the demand for alternative protein will instigate a reassessment of the global food system, with sustainability being a new focal point, using evaluation methods that are not yet entirely clear.

Alternatives for low- and middle-income countries are especially difficult. Consumers in nations that have only recently improved incomes embrace meat as a correlate of wealth and status. Moreover, long-standing traditions around maintenance of livestock in rural cultures are not likely to change quickly (Parlasca et al., 2023). In contrast, consumption of meat in OECD nations has languished or in certain instances has even dropped (Onwezen et al., 2021). Increasing availability of alternative proteins will almost certainly affect conventional trading relations and affect rural communities in poorer nations in unpredictable, but significant ways.

Alternative protein development can be categorized into multiple pillars: plant-based protein as substitutes for animal protein, precision fermentation using microbes to produce animal ingredient proteins, fermentation with the goal of modifying taste and structure of plant based food, production of microbial biomass for food, and cell-based (cultivated) meat. These innovations in food and agriculture will significantly unsettle the international market (Lee et al., 2023). The following review describes the origins and current status of these three technologies, and proceeds to explore how they will impact inequality, food sovereignty and the prospects for social justice. The review discusses the challenge of consumer acceptance to meat alternatives and concludes with a forecast of future directions for this growing market.

An overview of alternative proteins

Plant-based protein such as seitan from wheat, or tofu or tempeh from soy, have been produced in Asian countries and consumed for centuries. This form of protein gained popularity in the late-twenteeth Century in Western countries. Plant-based protein is both traditional and novel. Increased interest in new foods based on plant products with nutritional benefits and sensory attributes resonate for consumers today. Food innovations can be characterized as maintaining the taste and texture that makes them as satiating as animal-based products.

More lately, a rekindled interest in powders and energy bars with high protein content, has become a fashionable trend in food products (Allied Market Research, 2022). Protein sourced from plants alone can transform meat-centric meals into nutrient-rich, healthy alternatives (Sexton et al., 2019). Alternative protein products that can have the same look, taste and mouthfeel as animal-sourced foods is the latest development, and allows the consumer to retain the sensory pleasures of meat and dairy that they know and love, in particular when price levels are different. Currently, plant-based products with a similar mouthfeel such as sausage and hamburger are produced using pea and soy protein, by companies such as Impossible Food and Beyond Meat. Plant proteins extracted from these crops are then mixed with additional ingredients and processed into a meaty texture (Sexton et al., 2019).

Functional analogs are needed to produce plant-based replacements for animal proteins. First, crops with the necessary ingredients (proteins, fats, and starches) must be identified and processed. Second, processing must reformat ingredients into a muscle-like texture that resembles meat. Product formulation to get the preferred taste and texture, yet retain the desired nutritional qualities may consist of manufacturing processes such as extrusion, kneading, and 3D printing, among others (Specht, 2022).

An overview of fermentation

Fermentation has had a place in our diets since the beginning of mankind. From yogurt to beer, cultures of microbes have been put to work to preserve food products, as well as improve nutritional content and taste. Fermentation is traditionally used to obtain umami taste in cereal and pulse-based foods such as soya sauce, tempeh or miso (Li and Siddique, 2018). Umami is otherwise provided by animal sourced foods (Walsh et al., 2020; Mouritsen and Styrbæk, 2021; Gao et al., 2022; Li et al., 2022; Wang et al., 2022), or in traditional cuisines (such as the Mediterranean) by combining onion, garlic, and tomato in preparations like sofrito (Vallverdú-Queralt et al., 2013). From a functional perspective, fermentation also facilitates the digestion of complex carbohydrates from cereals and pulses. Fermentation further contributes to enhanced taste in plant-based dairy alternatives (Tangyu et al., 2019), which are more likely to be consumed by women (Pandey and Ritz, 2021).

Fermentation as a technology has been used over the years for disciplines ranging from biofuel production to pharmaceuticals (Ciani et al., 2021). Fermentation is currently used to generate novel foods, such as proteins from non-animal sources (Li and

Siddique, 2018). Established use of fermentation comprises lactic acid bacteria to produce cheese and yogurt, and fungi to ferment soy into tempeh. Microbial biomass alone can be used to make the food product, in certain circumstances. For example, the mycelium based products of the company Quorn^{TM}, operating since 1985, are based upon filamentous fungi, which are grown in microbial bioreactors. Products generated require minimal processing and are extremely nutritious. Quorn makes use of food waste to produce its products, using mycelium specific fermenters, and creates a carbon footprint one tenth lower than beef (Quorn Press Release, 2020). This fungal company has a global retail sale of over $200 million USD and produces 25,000 tons (dry mass) per year. It is no surprise that mycoprotein is projected to increase annually by 20% as a source of commercial food protein (Cherta-Murillo and Frost, 2021). Precision fermentation makes use of genetic engineering to create novel pigments, flavorings, and proteins via microbes. Impossible Foods makes a plant based version of a hamburger with the heme protein included via precision fermentation (Ciani et al., 2021).

Controlled bioreactors used to cultivate microbes such as fungi or bacteria and generate either biomass or specific food ingredients would be significantly more efficient than the open field growth of crops. The carbon footprint of bioreactors is low; moreover, they can be built no non-arable land or within city centers reduces competition for arable land. Production can even take place in industrial zones, where CO_2, H_2 and other inorganic carbon sources could be utilized (Airprotein.com, Järviö et al., 2021).

An overview of cultivated meat production

Cultivated/cell-based meat as a science is approaching two-decades of laboratory research, with its origins in the pharmaceutical and biomedical industries. The technical compatibilities and prospects seem encouraging. As important is the question of how socio-cultural framings serve to alter, accelerate or impede cultivated meat to global acceptance and coverage. This trajectory can be thought of in terms of two critical waves, the first initiated by university-based projects that were initially driven by ethical concerns for animal welfare, culminating in a slowly but steadily growing knowledge base in the field. The second was concern for environmental sustainability, notably supported in part by philanthropy.

In 2011, a New Yorker article reported that the technology for cultivated meat was available at that time but lacked sufficient funding (Spectre, 2011). Shortly afterwards, philanthropic donors financed the development of the first lab grown burger at Maastricht University (O'Riordan et al., 2017). The cultivated meat space was quickly supported via investments by wealthy funders with a focus on breakthrough technologies which could address global challenges. The industry shifted again to a third stage with investments from corporations such as Cargill or other food multinationals, Tyson Foods and Nestle, since 2017. New companies have moved in as well, such as Memphis Meats (which raised 17 million dollars in Series A funding). Eat Just Inc (2020), the first cell-based meat company with regulatory approval and housed in Singapore, has cell based chicken out on the market in 2023 (EatJust.com). The Israeli startup Aleph Farms has also moved forward, bringing slices or whole-meat cuts based on cultivated meat to the marketplace.

The development of cultivated meat products that are dependable with respect to taste and texture requires multiple types of cells, including fat cells, muscle precursor cells and connective tissue (O'Neill et al., 2021). The choice of medium used for production can also have an impact on meat quality and taste. The cultivated meat industry has to date concentrated on two major products: the first being unstructured, such as sausage or hamburger, and the second being highly structured, such as chicken breasts or beefsteaks. Achieving the latter requires the use of stem cells grown for 40–50 generations in a bioreactor, with the media changed at certain points to promote proliferation into muscle, fat and connective tissue. Differentiated cells such as these are adherent and require attachment to a scaffold; as a result, new biomaterials, such as collagen and egg shell membranes, have been acquired which play the role of microcarriers (Andreassen et al., 2022). The sera used must be free of any animal product and have features that are food-grade acceptable (Hanga et al., 2020).

Animal cell culture requires carbon and nitrogen, as well as amino acids, sugars, salts, and growth factors in order to proliferate (Yao and Asayama, 2017). These components influence sensory properties, for example, umami can be created from the amino acids asparagine and glutamic acid (Kawai et al., 2002). The way that media is prepared will impact how muscle cells proliferate and differentiate in culture. As an example, myoblasts need distinct cytokines and growth factors to proliferate, including fibroblast growth factor, insulin growth factor, hepatocyte growth factor, transforming growth factor-β and cytokines such as tumor necrosis factor-α (Bentzinger et al., 2010). These signaling molecules are able to stimulate myogenesis through various metabolic pathways and are currently prohibitively expensive. One way to reduce the cost of animal-derived growth factors is to screen for sequence homology with their plant or fungal counterparts. Extracts of chickpea peptides, for example, can stimulate insulin associated cell signaling (Girón-Calle et al., 2008). In the long run, it will be critical to replace animal serum with media that lacks animal-sourced products. It may be possible to utilize other, complex ingredients to reproduce constituents of media, such as the use of molasses, in place of purified glucose (Lee et al., 2022).

To create cultivated meat products such as steaks and chicken breasts *in vitro*, a natural, edible scaffold framework must be established that recreates the microenvironment that cells adhere to Bhat et al. (2017). The scaffold is necessary for cell cultivation and must be biocompatible with the cells so that they can proliferate while still enabling the free flow of nutrients and oxygen. Scaffolds can be made by electrospinning (a technique used to conform a solution of polymers into a network of fibers), mold cast/ injectable systems (in which "bioink," comprised of cultured cells, is injected into a mold that resembles a cut of meat), and 3D extrusion printing (in which bioink is placed on an extruder, which is itself constantly moving, to create a product more like ground meat) (GFI.org, 2022; Lee et al., 2022).

Under a laboratory setting, a 2D system comprised of Petri dishes and/or tissue culture flasks offers mechanical support for cells; however, the muscle cells undergo altered gene expression and thus change their phenotypic properties and behaviors. Over time, the cells take the form of a monolayer and cannot be sustained indefinitely. Alternatively, a 3D scaffold matrix comprised of a hydrogel of crosslinked hydrophilic polymers as well as growth factors incorporated into cell adhesive molecules, can better functionalize muscle cells for cultivated meat (Li et al., 2022). For scale up, cell cultures that are supported by microcarriers are needed to reach the volumes required to satisfy market demand. These microcarriers could dissolve over time, be edible, or be readily extractable during processing (Lee et al., 2022). Microcarriers could also encapsulate growth factors, which are later released to promote cell proliferation or differentiation over time. For example, Mosa Meats uses a technology to grow cultured meat by incorporating pillars which scaffold the materialization of a hydrogel containing muscle cells (Post, 2013). These muscle cells then self-assemble to form contractable rings in order to foster skeletal muscle maturation.

The hard limit to cell division is a major challenge; cells eventually enter a phase of senescence after undergoing a specified number of divisions. The number of cell divisions could be extended by including the enzyme telomerase (Kumar et al., 2021). The requirement for animal free media is another challenge. Prior to the development of the cultivated meat industry, animal derived serum—such as fetal calf serum—has been used. To address animal welfare concerns, serum free media, containing animal serum replacements will be necessary (van der Valk et al., 2018). For example, since serum contains insulin, a recombinant version produced in microbial bioreactors can replaced its animal counterpart. As an example, the animal protein albumin could be replaced with analogous proteins from plant sources, such as the albumin storage proteins (Bueno-Díaz et al., 2021).

Research and development of cell based meat activates new interest across various disciplines: identifying stem cells from different types of livestock, the development of scaffolds, increasing the proliferation and differentiation of cells in culture, scaling up processes and the production of fetal bovine serum-free growth media from alternative sources such as plants and fungi. Increasing manufacturing would also demand additional, more physical challenges, such as enabling animal cell culture in a large bioreactor to withstand shear stresses (Seah et al., 2022). Attitudinal factors will play a major role in acceptance, whatever the technical advances. Chief among these are complicated relationships among consumer perceptions regarding animal welfare as well as the dietary health benefits/risks of continuing to consume animal products. Economics matters as well: it is possible that production costs may never be low enough to make cultivated meat a generalizable option. It is equally likely that plant-based products that substitute for meat, such as the Impossible Burger, may develop in sophistication to such an extent that cultivated meat becomes obsolete (Warner, 2019).

Other sources of protein

Unconventional crops offer another potential alternative for food and fodder production. Cattle, sheep and other ruminants can feed on both duckweed or microalgae (Domokos-Szabolcsy et al., 2023; Paterson et al., 2023). These high yielding crops generate economically competitive forms of fiber and protein, and yet will not compete with arable land needed for human food in the food industry, algae is frequently found both as a functional food and as a food supplement (Scieszka and Klewicka, 2019). For example, spirulina, an cyanobacteria, can also be used as an upcoming food product (Grosshagauer et al., 2020).

Insects can also be consumed as a protein source. Edible insects are high in nutritional composition yet have the ability to reduce both land use as well as the carbon footprint (Poma et al., 2017; FAO, 2021). Entomophagy was part of the early history of humans—for example, over 3,000 years in China—but has only recently become a strong trend in Western culture. In over one hundred countries, about 2 billion people practice entomophagy today (Barennes et al., 2015; Jongema, 2022). Insects have a substantial protein content, and can thus represent an unconventional substitute for human consumption. Several insect peptides that reside in food products contain anti-hypertensive, anti-microbial and antioxidant properties, contributing important health advantages (de Castro et al., 2018; Hall et al., 2018). The next challenge to be addressed is the creation of large-scale facilities for edible insect production, whereas cultural barriers to expanding consumption are significant but perhaps changeable (da Silva Lucas et al., 2020).

Circular food systems

In a circular food system, green technologies utilize food waste and reduce pressure on arable farmland. Alternative protein production can play a role in this process. Land use for livestock feed has been examined in terms of acreage required for grazing and acreage needed to produce feed crops. In the case of alternative protein, land would still be needed to generate feedstock. Yet, if we made our feedstock from microalgae instead of food crops on arable land, our land usage needed could be even further reduced (Lusk and Norwood, 2009; Rubio et al., 2020). In a similar fashion, proteins that are derived from insects can be produced using food waste residue in place of arable land (Barennes et al., 2015; da Silva Lucas et al., 2020).

Precision fermentation systems utilize microbial bioreactors to produce their products. As a result, these fermentors require glucose from grain crops to feed the cell cultures. These more often are corn or sugar beet and thus waste much needed arable land. The avoidance of conventional sugar carbon sources using autotrophic microbes have been used in bioreactors to produce food proteins. Since the gases CO_2 or CH_4 can be used as a feed source for these microbes, the actual waste from industrial plants can be used as the feedstock (Järviö et al., 2021). Net use of greenhouse gas emissions could be achieved in this way, increasing the environmental sustainability factor. The great advantage of this form of fermentation is complete independence from outdoor agriculture in terms of food and biofuel and from fossil fuel. An additional benefit is reduction of vulnerability to the economic fluctuations that govern our current energy and food systems (Verstraete et al., 2022). Although alternative protein production is still at an early stage, it is developing rapidly (Parodi et al., 2018; Pikaar et al., 2018; Tuomisto, 2019).

Social justice and the alternative protein landscape

The effect of the alternative food protein revolution on world agriculture is uncertain (Stephens et al., 2019). While intensive farming, particularly of livestock, is thought by some to be leading to environmental catastrophe, the way that a major shift to animal protein replacements might affect the life of farmers and others in the animal-sourced foods industry, as well as those who produce animal feed, is uncertain. Disruptive technologies such as cultivated meat and precision fermentation offer promise for resolving both environmental and animal welfare issues that remain problematic within our current food system (Sexton et al., 2019). It is estimated that this revolution to non-animal sourced meat will lead to the rewilding and reforestation of land previously used for farming, and the restoration of ecosystems. But questions on economic sustainability and resilience remain: what changes will we see in the global marketplace? How will livelihoods be altered in rural settings? And how will regional discrepancies in meat production and consumption, as well as development and uptake of these innovations, affect global agri-food systems?

Approval of food proteins that are not animal-sourced will change from one country the next, and from culture to culture (FAO, 2022). Asia provides some real optimism; there has been greater consumer acceptance of protein from novel sources in India and China, for example, than in the US (Bekker et al., 2017). India as a subcontinent of many cultures is well known for being largely vegetarian, and as a result, the acceptance of technologies with respect to novel food products remains unclear. Political priorities matter, as well. Both animal welfare as well as environmental sustainability issues are coming to the forefront more quickly in certain political systems and not in others. Livestock maintained in American or European agriculture differ substantially than those managed in India or Latin America. For example, sub-Saharan owners of livestock could maintain a nomadic lifestyle and care for small herds of animals, whereas American livestock owners might manage tens of thousands of animals under industrial conditions. Differences arise in terms of the management of infectious disease pressures or the food safety of animal products, including use of antibiotics (Stevens et al., 2022). In the Americas for example, much environmental degradation has occurred in regions such as the Amazonian Forest, the Chaco region and the plains in Argentina, in order to produce either livestock for meat or the feedstock required to maintain them.

Industrialized countries exhibit the most readiness to develop and support alternative sources of animal protein (Hopkins et al., 2023). A colonial heritage with trade dependence means that richer countries have traditionally influenced food production beliefs and behavior in low- and middle-income trading partners (Paarlberg, 2009). Will nations long disadvantaged by the global economic system accept pressures to follow the inclinations of more industrialized countries or assert divergent cultural values associated with livestock production, as increased national income leads to increased demands for animal meat (Sexton et al., 2019)? How will these changes impact the global market with respect to imbalances between the Global North and South (Jarosz, 2011)? Might alternative proteins help to achieve food security and further develop the economies of low- and middle-income countries? Little research currently available sheds light on these difficult challenges (Tilman and Clark, 2014). Whereas, plant-based consumers experience new sensory experiences from a diversity of plant sources, consumers of animal sourced foods tend to be attached to the taste of meat (Perez-Cueto, 2020).

Consumer behavior toward the alternative protein movement

The increased attention toward novel foods with environmental benefits at policy and industry level has led to a large body of consumer studies on environmental-friendly foods (Vermeir et al., 2020)—such as plant-based alternative proteins (Aschemann-Witzel et al., 2021); cultured meat (Bryant and Barnett, 2018); and algae, pulses, and insects (Hartmann and Siegrist, 2017; Onwezen et al., 2022).

Plant-based diets are those diets that privilege foods of plant origin. Such diets go from vegan to flexitarian. Vegan diets exclude any type of foods of animal or insect origin. Vegetarian diets vary depending on whether they include dairy (lacto-vegetarian), eggs and dairy (lacto-ovo vegetarian), fish (pescetarian) or small amounts of meat and other foods of animal origin (flexitarian). Omnivores, however, can eat all foods consumed by the other dietary lifestyles.

Most consumer surveys show that few people (about 5%) following vegetarian diets (including vegans) (e.g., Pieniak et al., 2009; Pérez-Cueto et al., 2010; Verbeke et al., 2011); few in this group were complying with nutritional recommendations (Pérez-Cueto et al., 2012). Attempts to define this dietary lifestyle were made (Derbyshire, 2017), but revealed the complexity of the behavior and its implications. Flexitarian is a "flexible" term, coined for Millennials that prefer not being classified in limiting boxes, and that can include people within a very large range of consumption, from low or null meat and dairy intake to even heavy animal sourced food consumers. By 2021, at least one third of mainstream consumers identify themselves as flexitarians according to a recent EU consumer survey. These flexitarians expressed a common desire to eat more sustainably and adhere to ethical principles of consumption (Bechtold et al., 2022). The use of the term plant-based has been advocated as a neutral term (Faber et al., 2020; Storz, 2022) that is free from ideological tones (Dickstein et al., 2022), but the definition of a "plant-based" diet is unclear. For many, it is equivalent to vegan diet choices, whereas to others it is equivalent to a flexitarian eating lifestyle (Faber et al., 2020; Onwezen et al., 2021; Palmieri and Nervo, 2023; Takeda et al., 2023).

Traditional diets in Europe historically were largely vegetarian (Leggett and Lambert, 2022). It was only in the past 100 years that the society turned to predominantly meat and dairy consumption, partly because of increasing income, food security policy measures, and later by the effects of Common Agricultural Policy (CAP). Dietary recommendations have also been instrumental in supporting the belief that protein of animal origin is of superior quality when paired with varied consumption of fruits, vegetables and pulses. Urgent calls for healthier and more sustainable eating practices are met with both consumer inertia

(Willet et al., 2019; Vaidyanathan, 2021) and pressure from interest groups (Sievert et al., 2021).

Despite these obstacles, it is clear that transitioning to less meat-intensive diets could aid in reducing chronic disease due to poor dietary habits and contribute to mitigating climate change (Vaidyanathan, 2021). Factors that influence progress on the specific issue of replacing meat with alternative protein—besides animal welfare and environmental considerations – are age, gender, education and health status. Other motivators consist of cost, trust in science/neophobia, media coverage and convenience. The plant-based alternatives are the most well-established meat substitutes, as consumers are already familiar with them (Schosler et al., 2015).

A summary picture of consumers of alternative protein includes highly educated, young, left-leaning urbanites (De Boer and Aiking, 2011) and those who already consume little or no meat (Verbeke et al., 2011). Drivers pertaining to consumer acceptance include health and environmental benefits, convenience, familiarity and appearance and taste (Eckl et al., 2021). Women in general are more prone to adopt to plant-based diets (Nakagawa and Hart, 2019; Satija et al., 2019). Commonly known barriers to adopting plant-based diets include lack of skills, cognition about balanced eating, perceived hardships such as finding meal options when eating out, finding recipes, as well as perceptions of the inadequacy and tastelessness of a meatless diet (Pohjolainen et al., 2015; Reipurth et al., 2019; Hielkema and Lund, 2021).

While consumer acceptance is greatest for plant-based alternatives and moderate for cultured meat, it is lowest for insect-based protein (Onwezen et al., 2022). Nevertheless, there is heterogeneity in consumer acceptance and willingness-to-pay for specific types of insects and insect-based foods across and within countries (Dagevos, 2021). Edible insects are challenging for Western culture, on the other hand, cell-based meat is not yet available in the market. Despite growing interest in Europe, with various insect types approved as novel foods, consumers are often reluctant to shift, resulting in lower acceptance rates of insects as food (Iannuzzi et al., 2019). Yet reports indicate that higher willingness to consume shredded insect products rather than whole insects. However, for mainstream EU consumers, insects are the most distrusted (Smart Protein, 2021) and least accepted alternative protein (Onwezen et al., 2022), despite the growing number of approvals of insect types as novel foods. The demand to understand what drives consumer acceptance of such alternative proteins is paramount (Slade, 2018). Several barriers have been identified to explain this, such as cultural influences (e.g., insects might be viewed as pest insects), health and safety concerns (e.g., unsafe and causing diseases), negative sensory perceptions (e.g., flavor, appearance, texture) and attitudes (e.g., about sustainability, neophobia) (Van Huis, 2013). However, exposure and positive tasting experiences have shown to stimulate adoption of insect-based food products, especially in Western countries (Wendin and Nyberg, 2021). Price sensitivity is variable; consumers are typically willing to pay for insect-based products, especially if information on benefits is presented. If not, or if the insects are visible, consumers often prefer a price that is equal to, or lower than conventional products (de-Magistris et al., 2015; Kornher and Schellhorn, 2019; Lombardi et al., 2019). While insect-based foods are increasingly promoted, overall acceptance in regions where insects are not part of traditional consumption patterns is expected to be longer than for other alternative protein sources and will require (Francekonić et al., 2021) increased efforts to overcome barriers of familiarity, taste and emotional connotations (Ardoin and Prinyawiwatkul, 2021).

Cultured meat presents a different picture. An increasing number of products are projected to hit the market in the coming years, leading to growth in consumer research on cultured meat, especially after Eat Just became the first commercialized product in Singapore in 2020. In their systematic reviews, Bryant and Barnett (2018, 2020) demonstrated that cultured meat would be positively embraced by a large share of consumer populations, as illustrated by their willingness to try and buy, though not necessarily as a permanent replacement of conventional meat. Aside from regional and country differences, acceptance of cultured meat currently appeals to the group of young, highly educated, males (Bryant and Barnett, 2020), as well as non-vegetarians (Verbeke et al., 2021) or frequent meat consumers (Baum et al., 2022). Research shows that people who frequently consume large amounts of meat also show a higher level of acceptance of cell based meat (Stevens et al., 2022) in addition to other similar products (Hoek et al., 2011). Furthermore, consumers' perceived benefits were generally driven by societal benefits (e.g., animal and environmental) while perceived barriers were often linked to their personal risks (e.g., naturalness, safety and health, trust, technology neophobia) (Bryant and Barnett, 2018; Chriki and Jean-François, 2020). Highlighting these benefits (Bryant and Dillard, 2019; Gómez-Luciano et al., 2019) by utilizing counter-messaging (targeting conventional meat production issues to promote cultured meat) (Baum et al., 2022) positively influence consumer acceptance. Terminology preference (e.g., "clean meat") might also play a role (Bryant and Barnett, 2020), though this was not found in earlier studies (Verbeke et al., 2021). Nevertheless, price and taste expectations and evaluations of cultured meat products will continue to play a dominant role in consumers' decision making, similar as for other alternative protein sources.

The conclusion to draw from this section is not surprising: dietary habits are notably sticky and difficult to alter, hence notably slow and incremental. Nevertheless, it is clear that further development of alternatives and increasing concerns for human and environmental health are altering the potential.

Future prospects for alternative protein development

This review has presented the three major domains of alternative protein development. The ways that disruptive technologies involving alternative protein may influence consumer behavior, trade, and international inequalities are described as well. The increase in meat consumption per capita is most striking in countries that have increased in wealth, and a substantial middle class desirous of markers of affluence, including animal sourced products. Consumer behavior and willingness-to-pay will be important for aligning the future development of alternative protein products to potential target markets. In the future advancement of the three alternatives to meat proteins will concentrate on safety, perceived healthiness, taste, price and nutritional benefits and/or greater environmental friendliness.

Although alternative proteins have elicited much interest on a global scale, much effort will be required at multiple stages along the food supply chain. To start with, global warming is already affecting the yields in Southern Europe, and for some crops reducing their nutrient content; it will also create an opportunity for production in Northern Europe, to the detriment of existing forests. Improvements in crop breeding will be required, to increase the number of varieties with increased levels of high-quality protein, for plant-based meat production, Similarly, the removal of off-flavors and improved sensory characteristics—particularly taste and texture –will be critical (Specht, 2022). To mimic the red to brown change in color while cooking, improvements in color indicators for plant-based meat are also essential, and changes such as these will in turn lead to higher consumer acceptance.

Facility layout and operation will be critical for the cultivated meat industry. Today, the global market in meat products is over $800 billion; to produce quantities sufficient to capture a portion of that necessitates substantial scaling up of current infrastructure (Statista, 2022). The production of cultivated meat products with texture and taste that closely resemble conventional chicken breasts, beefsteaks or fish filets will be challenging. Because these represent newly emerging technologies, winning over consumers will require educational information about cultivated meat (Specht, 2022). Focusing on perceived benefits (Verbeke et al., 2021), especially through leveraging problems of conventional meat production to build the case for cultured meat (Baum et al., 2022), appear to influence acceptance.

Microbial bioreactors will also require development for the adequate fermentation of animal proteins. These will include the development of new microbial strains that can perform tasks with greater precision and result in better taste, as will be the identification of new feedstocks that could be optimized for fossil fuel independent production pathways that are also not reliant upon crop production. Bioreactors could in the future be used to produce green industrial products that are not only petroleum independent, but in fact make use of greenhouse gases such as CO_2 and CH_4 for their feedstock, thus making them carbon negative in production (Järviö et al., 2021).

While cultivated meat and precision fermentation each require bioreactors for cell growth, animal cells proliferate much more slowly than microbes, and may generate growth-inhibiting catabolites such as ammonia during the incubation process (O'Neill et al., 2021). Since animal cells lack a cell wall, they are also more likely to be damaged. For animal cells, different types of culture are needed to recreate complex forms of meat, with bioreactor design and tailored media requirements being essential for this task (Ben-Arye and Levenberg, 2019). The total capital investment estimated today per kg for cultured meat using a perfusion bioreactor is $51 while a bioreactor with a fed-batch design have been determined at a total cost of $37. Consumers have demonstrated a willingness to pay for cultured meat at a cost limitation of $25 per kg. After further packaging, and distribution, a minimum of $50 per kg for cultured meat is estimated for supermarket settings, making advancements a significant challenge (Humbird, 2021).

In sum, multiple questions concerning practicality and cost emerge from the specifics of alternative production techniques and products. These questions point the way to intelligent choices of both research and funding.

Conclusion

This review has addressed possible futures for alternative proteins, with a view toward alleviating the current climate crisis and avoiding injustice in the transition to a more sustainable food system. Though research into and development of animal protein replacements has produced an explosion of innovation, dietary habits are notably sticky and difficult to alter, hence notably slow and incremental.

Different technologies have been reviewed with their attendant products. Technological limitations and safety issues along the production chain suggest that cultivated meat and insect protein offer attractive prospects but will likely advance slowly for some time. From the current consumer perspective, plant-based proteins are preferred, although there are challenges for product development throughout the chain. Fermented foods will gain more attention in the coming years as they provide desired flavor and textures. For all of these elements of a new food system to be successful, both public and private funding will need priority tags and informed choices, but with ramifying benefits. Reducing the financial investment necessary to produce plant-based meat and thus decreasing costs would render plant-based meat production more viable in less affluent countries, contributing to enhancement of global justice and environmental sustainability. Success in expanding production and use of alternative proteins will involve an amalgamation of specific solutions – not a silver bullet—and changes in attitudes about production and consumption of food discussed in this essay.

Author contributions

KH: Conceptualization, Methodology, Investigation, Writing—original draft preparation, Writing—review & Editing. HD: Investigation, Writing—review & Editing; FP-C: Investigation, Writing—review & Editing; RH: Investigation, Writing—review & Editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Aimutis, W. R. (2022). Plant-based proteins: the good, bad, and ugly. *Annu. Rev. Food Sci. Technol*. 13, 1–17. doi: 10.1146/annurev-food-092221-041723

Allied Market Research (2022). Available online at: https://www.alliedmarketresearch.com/press-release/protein-supplement-market.html (accessed April 3, 2022).

Andreassen, R. C., Rønning, S. B., Solberg, N. T., Grønlien, K. G., Kristoffersen, K. A., Høst, V., et al. (2022). Production of food-grade microcarriers based on by-products from the food industry to facilitate the expansion of bovine skeletal muscle satellite cells for cultured meat production. *Biomaterials* 286, 121602. doi: 10.1016/j.biomaterials.2022.121602

Ardoin, R., and Prinyawiwatkul, W. (2021). Consumer perceptions of insect consumption: a review of western research since 2015. *Int. J. Food Sci. Technol.* 56, 4942–4958. doi: 10.1111/ijfs.15167

Aschemann-Witzel, J., Gantriis, R. F., Fraga, P., and Perez-Cueto, F. J. A. (2021). Plant-based food and protein trend from a business perspective: markets, consumers, and the challenges and opportunities in the future. *Crit. Rev. Food Sci. Nutr.* 61, 3119–3128. doi: 10.1080/10408398.2020.1793730

Barennes, H., Phimmasane, M., and Rajaonarivo, C. (2015).Insect consumption to address undernutrition, a national survey on the prevalence of insect consumption among adults and vendors in Laos. *PLoS ONE* 10, e0136458. doi: 10.1371/journal.pone.0136458

Baum, C. M., Verbeke, W., and De Steur, H. (2022). Turning your weakness into my strength: how counter-messaging on conventional meat influences acceptance of cultured meat. *Food Quality Pref.* 97, 104485. doi: 10.1016/j.foodqual.2021.104485

Bechtold, M. L., Brown, P. M., Escuro, A., Grenda, B., Johnston, T., Kozeniecki, M., et al. (2022). When is enteral nutrition indicated? *J. Parenter. Enteral Nutr.* 46, 1470–1496. doi: 10.1002/jpen.2364

Bekker, G. A., Tobi, H., and Fischer, A. R. (2017). Meet meat: an explorative study on meat and cultured meat as seen by Chinese, Ethiopians and Dutch. *Appetite* 114, 82–92. doi: 10.1016/j.appet.2017.03.009

Ben-Arye, T., and Levenberg, S. (2019). Tissue engineering for clean meat production. *Front. Sustain. Food Syst*. 3:46. doi: 10.3389/fsufs.2019.00046

Bentzinger, C. F., von Maltzahn, J., and Rudnicki, M. A. (2010). Extrinsic regulation of satellite cell specification. *Stem Cell Res. Ther*. 1, 27. doi: 10.1186/scrt27

Bhat, Z. F., Kumar, S., and Bhat, H. F. (2017). *In vitro* meat: a future animal-free harvest. *Crit. Rev. Food Sci. Nutr.* 57, 782–789. doi: 10.1080/10408398.2014.924899

Bryant, C., and Barnett, J. (2018). Consumer acceptance of cultured meat: a systematic review. *Meat Sci.* 143, 8–17. doi: 10.1016/j.meatsci.2018.04.008

Bryant, C., and Barnett, J. (2020). Consumer acceptance of cultured meat: an updated review (2018–2020). *Appl. Sci.* 10, 5201. doi: 10.3390/app10155201

Bryant, C., and Dillard, C. (2019). The impact of framing on acceptance of cultured meat. *Front. Nutr.* 6, 103. doi: 10.3389/fnut.2019.00103

Bueno-Díaz, C., Biserni, C., Martín-Pedraza, L., de Las Heras, M., Blanco, C., Vázquez-Cortés, S., et al. (2021). Seed storage proteins, 2s albumin and 11s globulin, associated to severe allergic reactions after flaxseed intake. *J. Investig. Allergol. Clin. Immunol.* 4, 713. doi: 10.18176/jiaci.0713

Chai, B. C., van der Voort, J. R., Grofelnik, K., Eliasdottir, H. G., Klöss, I., Perez-Cueto, F. J. A., et al. (2019). Which diet has the least environmental impact on our planet? A systematic review of vegan, vegetarian and omnivorous diets. *Sustainability* 11, 4110. doi: 10.3390/su11154110

Cherta-Murillo, A., and Frost, G. S. (2021). The association of mycoprotein-based food consumption with diet quality, energy intake and non-communicable diseases' risk in the UK adult population using the national diet and nutrition survey (NDNS) years 2008/2009-2016/2017: a cross-sectional study. *Br. J. Nutr.* 17, 1–10. doi: 10.1017/S000711452100218X

Chriki, S., and Jean-François, H. (2020). The myth of cultured meat: a review. *Front. Nutr.* 7, 7. doi: 10.3389/fnut.2020.00007

Ciani, M., Lippolis, A., Fava, F., Rodolfi, L., and Niccolai, A. (2021). Microbes: food for the future. *Foods* 10, 971. doi: 10.3390/foods10050971

da Silva Lucas, A. J., de Oliveira, L. M., Da Rocha, M., and Prentice, C. (2020). Edible insects: an alternative of nutritional, functional and bioactive compounds. *Food Chem.* 311, 126022. doi: 10.1016/j.foodchem.2019.126022

Dagevos, H. (2021). A literature review of consumer research on edible insects: Recent evidence and new vistas from 2019 studies. *J. Insects Food Feed* 7, 249–259. doi: 10.3920/JIFF2020.0052

De Boer, J., and Aiking, H. (2011). On the merits of plant-based proteins for global food security: marrying macro and micro perspectives. *Ecol. Econ.* 70, 1259–1265. doi: 10.1016/j.ecolecon.2011.03.001

de Castro, R. J. S., Ohara, A., dos Santos Aguilar, J. G., and Domingues, M. A. F. (2018). Nutritional, functional and biological properties of insect proteins: Processes for obtaining, consumption and future challenges. *Trends Food Sci. Technol.* 76, 82–89. doi: 10.1016/j.tifs.2018.04.006

de-Magistris, T., Pascucci, S., and Mitsopoulos, D. (2015). Paying to see a bug on my food: how regulations and information can hamper radical innovations in the European Union. *Br. Food J*. 117, 1777–1792. doi: 10.1108/BFJ-06-2014-0222

Derbyshire, E. J. (2017). Flexitarian diets and health: a review of the evidence-based literature. *Front Nutr.* 3, 55. doi: 10.3389/fnut.2016.00055

Dickstein, J., Dutkiewicz, J., and Guha-Majumdar, J. (2022). Veganism as left praxis. *Capitalism Nat. Soc.* 33, 56–75. doi: 10.1080/10455752.2020.1837895

Domokos-Szabolcsy, É., Yavuz, S. R., Picoli, E., Fári, M. G., Kovács, Z., Tóth, C., et al. (2023). Green biomass-based protein for sustainable feed and food supply: an overview of current and future prospective. *Life* 13, 307. doi: 10.3390/life13020307

Eat Just Inc (2020). *Gets Approval in Singapore for Lab-Grown Chicken.* Available online at: https://www.foodsafetynews.com/2020/12/eat-just-inc-gets-approval-in-singapore-for-lab-grown-chicken/ (accessed December 13, 2020).

Eckl, M. R., and Biesbroek, S., Van't Veer, P., and Geleijnse, J. M. (2021). Replacement of meat with non-meat protein sources: a review of the drivers and inhibitors in developed countries. *Nutrients* 13, 3602. doi: 10.3390/nu13103602

Faber, I., Castellanos-Feijoó, N. A., Van de Sompel, L., Davydova, A., and Perez-Cueto, F. J. A. (2020). Attitudes and knowledge towards plant-based diets of young adults across four European countries. Exploratory survey. *Appetite* 145, 104498. doi: 10.1016/j.appet.2019.104498

FAO (2021). *Looking at Edible Insects From a Food Safety Perspective. Challenges and Opportunities for the Sector*. Rome: FAO.

FAO (2022). *The Future of Food and Agriculture – Drivers and Triggers for Transformation. The Future of Food and Agriculture, no. 3.* Rome: FAO.

Fegan, N., and Jenson, I. (2018). The role of meat in foodborne disease: is there a coming revolution in risk assessment and management? *Meat Sci.* 144, 22–29. doi: 10.1016/j.meatsci.2018.04.018

Franceković, P., García-Torralba, L., Sakoulogeorga, E., Vučković, T., and Perez-Cueto, F. J. A. (2021). How do consumers perceive cultured meat in Croatia, Greece, and Spain? *Nutrients* 13, 1284. doi: 10.3390/nu13041284

Gao, B., Hu, X., Xue, H., Li, R., Liu, H., Han, T., et al. (2022). Isolation and screening of umami peptides from preserved egg yolk by nano-HPLC-MS/MS and molecular docking. *Food Chem.* 377, 131996. doi: 10.1016/j.foodchem.2021.131996

GFI.org (2022). Available online at: https://gfi.org/science/the-science-of-cultivated-meat/deep-dive-cultivated-meat-scaffolding/

Girón-Calle, J., Vioque, J., Pedroche, J., Alaiz, M., Yust, M. M., Megías, C., et al. (2008). Chickpea protein hydrolysate as a substitute for serum in cell culture. *Cytotechnology* 57, 263–272. doi: 10.1007/s10616-008-9170-z

Gómez-Luciano, C. A., De Aguiar, D., Vriesekoop, L. K., and Urbano, F. B. (2019). Consumers' willingness to purchase three alternatives to meat proteins in the United Kingdom, Spain, Brazil and the Dominican Republic. *Food Quality Pref.* 78, 103732. doi: 10.1016/j.foodqual.2019.103732

González, N., Marquès, M., Nadal, M., and Domingo, J. L. (2020). Meat consumption: which are the current global risks? A review of recent (2010–2020) evidences. *Food Res. Int.* 137, 109341. doi: 10.1016/j.foodres.2020.109341

Grosshagauer, S., Kraemer, K., and Somoza, V. (2020). The true value of spirulina. *J. Agric. Food Chem*. 68, 4109–4115. doi: 10.1021/acs.jafc.9b08251

Hall, F., Johnson, P. E., and Liceaga, A. (2018). Effect of enzymatic hydrolysis on bioactive properties and allergenicity of cricket (*Gryllodes sigillatus*) protein. *Food Chem.* 262, 39–47. doi: 10.1016/j.foodchem.2018.04.058

Hanga, M. P., Ali, J., Moutsatsou, P., de la Raga, F. A., Hewitt, C. J., Nienow, A., and Wall, I. (2020). Bioprocess development for scalable production of cultivated meat. *Biotechnol. Bioeng.* 117, 3029–3039. doi: 10.1002/bit.27469

Hartmann, C., and Siegrist, M. (2017). Consumer perception and behaviour regarding sustainable protein consumption: a systematic review. *Trends Food Sci. Technol.* 61, 11–25. doi: 10.1016/j.tifs.2016.12.006

Hielkema, M. H., and Lund, T. B. (2021). Reducing meat consumption in meat-loving Denmark: exploring willingness, behavior, barriers and drivers. *Food Quality Pref.* 93, 104257. doi: 10.1016/j.foodqual.2021.104257

Hoek, A. C., Luning, P. A., Weijzen, P., Engels, W., and Kok, F. J., Graaf, d. e., et al. C. (2011). Replacement of meat-by-meat substitutes. A survey on person- and product related factors in consumer acceptance. *Appetite* 56, 662–673. doi: 10.1016/j.appet.2011.02.001

Hopkins, I., Farahnaky, A., Gill, H., Danaher, J., and Newman, L. P. (2023). Food neophobia and its association with dietary choices and willingness to eat insects. *Front. Nutr.* 10, 1150789. doi: 10.3389/fnut.2023.1150789

Humbird, D. (2021). Scale-up economics for cultured meat. *Biotechnol. Bioeng*. 118, 3239–3250. doi: 10.1002/bit.27848

Iannuzzi, E., Sisto, R., and Nigro, C. (2019). The willingness to consume insect-based food: an empirical research on Italian consumers. *Agric. Econ.* 65, 454–462. doi: 10.17221/87/2019

Jarosz, L. (2011). Defining world hunger: scale and neoliberal ideology in international food security policy discourse. *Food Culture Soc.* 14, 117–139. doi: 10.2752/175174411X12810842291308

Järviö, N., Maljanen, N. L., Kobayashi, Y., Ryynänen, T., and Tuomisto, H. L. (2021). An attributional life cycle assessment of microbial protein production: a case study on using hydrogen-oxidizing bacteria. *Sci. Total Environ*. 776, 145764. doi: 10.1016/j.scitotenv.2021.145764

Jongema, Y. (2022). (2017). *List of Edible Insects of the World*. Wageningen, The Netherlands: Wageningen University.

Kawai, M., Okiyama, A., and Ueda, Y. (2002). Taste enhancements between various amino acids and IMP. *Chem. Senses* 27, 739–745. doi: 10.1093/chemse/27.8.739

Kornher, L., and Schellhorn, M. (2019). Disgusting or innovative-consumer willingness to pay for insect based burger patties in Germany. *Sustainability* 11, 1878. doi: 10.3390/su11071878

Kumar, P., Sharma, N., Sharma, S., Mehta, N., Verma, A. K., Chemmalar, S., et al. (2021). In-vitro meat: a promising solution for sustainability of meat sector. *J. Anim. Sci. Technol.* 63, 693–724. doi: 10.5187/jast.2021.e85

Lee, H. J., Kim, D. W., Kim, C., Ryu, H. D., Chung, E. G., Kim, K., et al. (2021). Concentrations and risk assessments of antibiotics in an urban-rural complex watershed with intensive livestock farming. *Int. J. Environ. Res. Pub. Health* 18, 10797. doi: 10.3390/ijerph182010797

Lee, K. Y., Loh, H. X., and Wan, A. C. (2022). Systems for muscle cell differentiation: from bioengineering to future food. *Micromachines* 13, 71. doi: 10.3390/mi13010071

Lee, S. Y., Lee, D. Y., Jeong, J. W., Kim, J. H., Yun, S. H., Mariano, E. J., et al. (2023). Current technologies, regulation, and future perspective of animal product analogs - A review. *Anim Biosci*. 36, 1465–1487. doi: 10.5713/ab.23.0029

Leggett, S., and Lambert, T. (2022). Food and power in early medieval England: a lack of (isotopic) enrichment. *Anglo-Saxon England* 24, 1–34. doi: 10.1017/S0263675122000072

Li, X., and Siddique, K. H. (2018). *Future Smart Food. Rediscovering Hidden Treasures of Neglected and Underutilized Species for Zero Hunger in Asia, Bangkok*. Rome: FAO.

Li, Z., Zhou, Y., Li, T., Zhang, J., and Tian, H. (2022). Stimuli-responsive hydrogels: fabrication and biomedical applications. *View* 3, 20200112. doi: 10.1002/VIW.20200112

Lima, M., Costa, R., Rodrigues, I., Lameiras, J., and Botelho, G. A. (2022). Narrative review of alternative protein sources: highlights on meat, fish, egg and dairy analogues. *Foods* 11, 2053. doi: 10.3390/foods11142053

Lombardi, A., Vecchio, R., Borrello, M., and Caracciolo, F. (2019). Willingness to pay for insect-based food: the role of information and carrier. *Food Q. Pref.* 72, 177–187. doi: 10.1016/j.foodqual.2018.10.001

Lusk, J., and Norwood, F. (2009). Some economic benefits and costs of vegetarianism. *Agric. Res. Econ. Rev*. 38, 109–124. doi: 10.1017/S1068280500003142

Micha, R., Wallace, S. K., and Mozaffarian, D. (2010). Red and processed meat consumption and risk of incident coronary heart disease, stroke, and diabetes mellitus: a systematic review and meta-analysis. *Circulation* 121, 2271–2283. doi: 10.1161/CIRCULATIONAHA.109.924977

Mouritsen, O. G., and Styrbæk, K. (2021). Design and 'umamification'of vegetable dishes for sustainable eating. *Int. J. Food Desig.* 5, 9–42. doi: 10.1386/ijfd_00008_1

Nakagawa, S., and Hart, C. (2019). Where's the beef? How masculinity exacerbates gender disparities in health behaviors. *Socius Sociol. Res. Dyn. World* 5, 237802311983180. doi: 10.1177/2378023119831801

O'Neill, E. N., Cosenza, Z. A., Baar, K., and Block, D. E. (2021). Considerations for the development of cost-effective cell culture media for cultivated meat production. *Compr Rev Food Sci Food Saf.* 20, 686–709. doi: 10.1111/1541-4337.12678

Onwezen, M. C., Bouwman, E. P., and Reinders, M. J. (2021). A systematic review on consumer acceptance of alternative proteins: pulses, algae, insects, plant-based meat alternatives, and cultured meat. *Appetite* 159, 105058. doi: 10.1016/j.appet.2020.105058

Onwezen, M. C., Verain, M. C. D., and Dagevos, H. (2022). Social norms support the protein transition: the relevance of social norms to explain increased acceptance of alternative protein burgers over 5 years. *Foods* 11, 3413. doi: 10.3390/foods11213413

O'Riordan, K., Fotopoulou, A., and Stephens, N. (2017). The first bite: imaginaries, promotional publics and the laboratory grown burger. *Pub. Understanding Sci.* 26, 148–163. doi: 10.1177/0963662516639001

Paarlberg, R. (2009). *Starved for Science: How Biotechnology is Being Kept Out of Africa*. Boston, MA: Harvard University Press.

Palmieri, N., and Nervo, C. (2023). Consumers' attitudes towards sustainable alternative protein sources: comparing seaweed, insects and jellyfish in Italy. *Food Q. Pref.* 104, 104735. doi: 10.1016/j.foodqual.2022.104735

Pandey, S., and Ritz, C. (2021). An application of the theory of planned behaviour to predict intention to consume plant-based yogurt alternatives. *Foods* 10, 148. doi: 10.3390/foods10010148

Parlasca, M., Knößlsdorfer, I., Alemayehu, G., and Doyle, R. (2023). How and why animal welfare concerns evolve in developing countries. *Anim. Front*. 13, 26–33. doi: 10.1093/af/vfac082

Parodi, A., Leip, A., De Boer, I. J. M., Slegers, P. M., Ziegler, F., Temme, E. H. (2018). The potential of future foods for sustainable and healthy diets. *Nat. Sustain.* 1, 782–789. doi: 10.1038/s41893-018-0189-7

Paterson, S., Gómez-Cortés, P., de la Fuente, M. A., and Hernández-Ledesma, B. (2023). Bioactivity and digestibility of microalgae tetraselmis sp. and nannochloropsis sp. as basis of their potential as novel functional foods. *Nutrients* 15, 477. doi: 10.3390/nu15020477

Perez-Cueto, F. J. (2020). Sustainability, health and consumer insights for plant-based food innovation. *Int. J. Food Design* 2, 139–148. doi: 10.1386/ijfd_00017_3

Pérez-Cueto, F. J., Aschemann-Witzel, J., Shankar, B., Brambila-Macias, J., and Bech-Larsen, T. (2012). Assessment of evaluations made to healthy eating policies in Europe: a review within the EATWELL Project. *Pub. Health Nutr*. 15, 1489–1496. doi: 10.1017/S1368980011003107

Pérez-Cueto, F. J., Verbeke, W., de Barcellos, M. D., Kehagia, O., Chryssochoidis, G., Scholderer, J., et al. (2010). Food-related lifestyles and their association to obesity in five European countries. *Appetite* 54, 156–162. doi: 10.1016/j.appet.2009.10.001

Perignon, M., and Darmon, N. (2022). Advantages and limitations of the methodological approaches used to study dietary shifts towards improved nutrition and sustainability. *Nutr. Rev*. 80, 579–597. doi: 10.1093/nutrit/nuab091

Pieniak, Z., Pérez-Cueto, F., and Verbeke, W. (2009). Association of overweight and obesity with interest in healthy eating, subjective health and perceived risk of chronic diseases in three European countries. *Appetite* 53, 399–406. doi: 10.1016/j.appet.2009.08.009

Pikaar, I., Matassa, S., Bodirsky, B. L., Weindl, I., Humpen?der, F., Rabaey, K. (2018). Decoupling livestock from land use through industrial feed production pathways. *Environ. Sci. Technol.* 52, 7351–7359. doi: 10.1021/acs.est.8b00216

Pohjolainen, P., Vinnari, M., and Jokinen, P. (2015). Consumers' perceived barriers to following a plant-based diet. *Br. Food J.* 117, 1150–1167. doi: 10.1108/BFJ-09-2013-0252

Poma, G., Cuykx, M., Amato, E., Calaprice, C., Focant, J. F., Covaci, A., et al. (2017). Evaluation of hazardous chemicals in edible insects and insect-based food intended for human consumption. *Food Chem. Toxicol.* 100, 70–79. doi: 10.1016/j.fct.2016.12.006

Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science* 360, 987–992. doi: 10.1126/science.aaq0216

Post, M. J. (2013). Cultured beef: medical technology to produce food. *J. Sci. Food Agric*. 94, 1039–1104. doi: 10.1002/jsfa.6474

Quorn Press Release (2020). Available online at: https://www.quorn.co.uk/company/press/quorn-unveils-carbon-footprint-labelling-of-its-products-and-calls-on-other#:~:text=In%202018%20alone%2C%20Quorn%20Foods,90%25%20lower%20than%20beef1 (accessed April 10, 2020).

Reipurth, M. F. S., Hørby, L., Gregersen, C. G., Bonke, A., and Perez Cueto, F. J. A. (2019). Barriers and facilitators towards adopting a more plant-based diet in a sample of Danish consumers. *Food Q. Pref.* 73, 288–292. doi: 10.1016/j.foodqual.2018.10.012

Rubio, N. R., Xiang, N., and Kaplan, D.L. (2020). Plant-based and cell-based approaches to meat production. *Nat. Commun.* 11, 6276. doi: 10.1038/s41467-020-20061-y

Satija, A., Malik, V., Rimm, E. B., Sacks, F., Willett, W., and Hu, F. B. (2019). Changes in intake of plant-based diets and weight change: results from 3 prospective cohort studies. *The Am. J. Clin. Nutr.* 110, 574–582. doi: 10.1093/ajcn/nqz049

Schosler, H., de Boer, J., Boersema, J. J., and Aiking, H. (2015). Meat and masculinity among young Chinese, Turkish and Dutch adults in the Netherlands. *Appetite* 89, 152–159.

Scieszka, S., and Klewicka, E. (2019). Algae in food: a general review. *Crit. Rev. Food Sci. Nutr*. 59, 3538–3547. doi: 10.1080/10408398.2018.1496319

Seah, J. S. H., Singh, S., Tan, L. P., and Choudhury, D. (2022). Scaffolds for the manufacture of cultured meat. *Crit. Rev. Biotechnol.* 42, 311–323. doi: 10.1080/07388551.2021.1931803

Sexton, A. E., Lorimer, J., and Garnett, T. (2019). Framing the future of food: the contested promises of alternative proteins. *Environ. Plan. E Nat. Space* 2, 47–72. doi: 10.1177/2514848619827009

Sievert, K., Lawrence, M., Parker, C., and Baker, P. (2021). Understanding the political challenge of red and processed meat reduction for healthy and sustainable food systems: a narrative review of the literature. *Int. J. Health Policy Manag.* 10, 793–808. doi: 10.34172/ijhpm.2020.238

Slade, P. (2018). If you build it, will they eat it? Consumer preferences for plant-based and cultured meat burgers. *Appetite* 125, 428–437. doi: 10.1016/j.appet.2018.02.030

Smart Protein (2021). *What Consumers Want: A Survey on European consumer Attitudes Towards Plant-Based Foods, With a Focus on Flexitarians', European Union's Horizon 2020 Research and Innovation Programme (No 862957).* Available online at: https://smartproteinproject.eu/wp-content/uploads/FINAL_Pan-EU-consumer-survey_Overall-Report-.pdf (accessed November 12, 2021).

Specht, L. (2022). *Good Food Intitute.org.* Available online at: https://gfi.org/science (accessed April 3, 2022).

Spectre, M. (2011). *Test Tube Burgers, The New Yorker*. Available online at: https://www.newyorker.com/magazine/2011/05/23/test-tube-burgers (accessed May 23, 2011).

Statista (2022). Available online at: https://www.statista.com/topics/4880/global-meat-industry/ (accessed April 3, 2022).

Stephens, N., Sexton, A. E., and Driessen, C. (2019). Making sense of making meat: key moments in the first 20 years of tissue engineering muscle to make food. *Front. Sust. Food Syst*. 3, 45. doi: 10.3389/fsufs.2019.00045

Stevens, G. A., Beal, T., Mbuya, M. N. N., Luo, H., Neufeld, L. M., and Global Micronutrient Deficiencies Research Group (2022). Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: a pooled analysis of individual-level data from population-representative surveys. *Lancet Glob. Health* 10, e1590–e1599. doi: 10.1016/S2214-109X(22)00367-9

Storz, M. A. (2022). What makes a plant-based diet? A review of current concepts and proposal for a standardized plant-based dietary intervention checklist. *Eur. J. Clin. Nutr*. 76, 789–800. doi: 10.1038/s41430-021-01023-z

Takeda, K. F., Yazawa, A., Yamaguchi, Y., and Koizumi, N. (2023). Comparison of public attitudes toward five alternative proteins in Japan. *Food Q. Pref.* 105, 104787. doi: 10.1016/j.foodqual.2022.104787

Tangyu, M., Muller, J., and Bolten, C. J. (2019). Fermentation of plant-based milk alternatives for improved flavour and nutritional value. *Appl. Microbiol. Biotechnol.* 103, 9263–9275. doi: 10.1007/s00253-019-10175-9

Tilman, D., and Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature* 515, 518–522. doi: 10.1038/nature13959

Tuomisto, H. L. (2019). The eco-friendly burger: Could cultured meat improve the environmental sustainability of meat products? *EMBO Rep*. 20, e47395. doi: 10.15252/embr.201847395

Vaidyanathan, G. (2021). What humanity should eat to stay healthy and save the planet. *Nature* 600, 22–25. doi: 10.1038/d41586-021-03565-5

Vallverdú-Queralt, A., de Alvarenga, J. F., Estruch, R., and Lamuela-Raventos, R. M. (2013). Bioactive compounds present in the Mediterranean sofrito. *Food Chem*. 141, 3365–3372. doi: 10.1016/j.foodchem.2013.06.032

van der Valk, J., Bieback, K., Buta, C., Cochrane, B., Dirks, W. G., Fu, J., et al. (2018). Fetal bovine serum (FBS): past - present - future. *ALTEX* 35, 99–118. doi: 10.14573/altex.1705101

Van Huis, A. (2013). Potential of insects as food and feed in assuring food security. *Ann. Rev. Entomol.* 58, 563–583. doi: 10.1146/annurev-ento-120811-153704

Verbeke, W., Hung, Y., and Baum, C. M. H. (2021). The power of initial perceived barriers versus motives shaping consumers' willingness to eat cultured meat as a substitute for conventional meat. *Livestock Sci.* 253, 104705. doi: 10.1016/j.livsci.2021.104705

Verbeke, W., Pérez-Cueto, F. J., and Grunert, K. G. (2011). To eat or not to eat pork, how frequently and how varied? Insights from the quantitative Q-PorkChains consumer survey in four European countries. *Meat Sci*. 88, 619–626. doi: 10.1016/j.meatsci.2011.02.016

Vermeir, I., Weijters, B., Houwer, D., e., Geuens, J., Slabbinck, M. and Spruyt, H. et al. (2020). Environmentally sustainable food consumption: a review and research agenda from a goal-directed perspective. *Front. Psychol.* 11, 1603. doi: 10.3389/fpsyg.2020.01603

Verstraete, W., Yanuka-Golub, K., Driesen, N., and De Vrieze, J. (2022). Engineering microbial technologies for environmental sustainability: choices to make. *Microb Biotechnol.* (2022) 15:215–227. doi: 10.1111/1751-7915.13986

Walsh, E. A., Diako, C., Smith, D. M., and Ross, C. F. (2020). Influence of storage time and elevated ripening temperature on the chemical and sensory properties of white Cheddar cheese. *J. Food Sci*. 85, 268–278. doi: 10.1111/1750-3841.14998

Wang, W., Huang, Y., Zhao, W., Dong, H., Yang, J., Bai, W., et al. (2022). Identification and comparison of umami-peptides in commercially available dry-cured Spanish mackerels (*Scomberomorus niphonius*). *Food Chem*. 380, 132175. doi: 10.1016/j.foodchem.2022.132175

Warner, R. (2019). Review: analysis of the processes ad drivers for cellular meat production. *Animal* 13, 3041–3058. doi: 10.1017/S1751731119001897

Wendin, K. M., and Nyberg, M. E. (2021). Factors influencing consumer perception and acceptability of insect-based foods. *Cur. Opin. Food Sci.* 40, 67–71. doi: 10.1016/j.cofs.2021.01.007

Willet, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *EAT Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Wolk, A. (2017). Potential health hazards of eating red meat. *J. Int. Med*. 281, 106–122. doi: 10.1111/joim.12543

World Health Organization (2022). Available online at: https://www.who.int/publications/m/item/the-state-of-food-security-and-nutrition-in-the-world-2021 (accessed April 3, 2022).

Yao, T., and Asayama, Y. (2017). Animal-cell culture media: history, characteristics, and current issues. *Reprod. Med. Biol*. 16, 99–117. doi: 10.1002/rmb2.12024

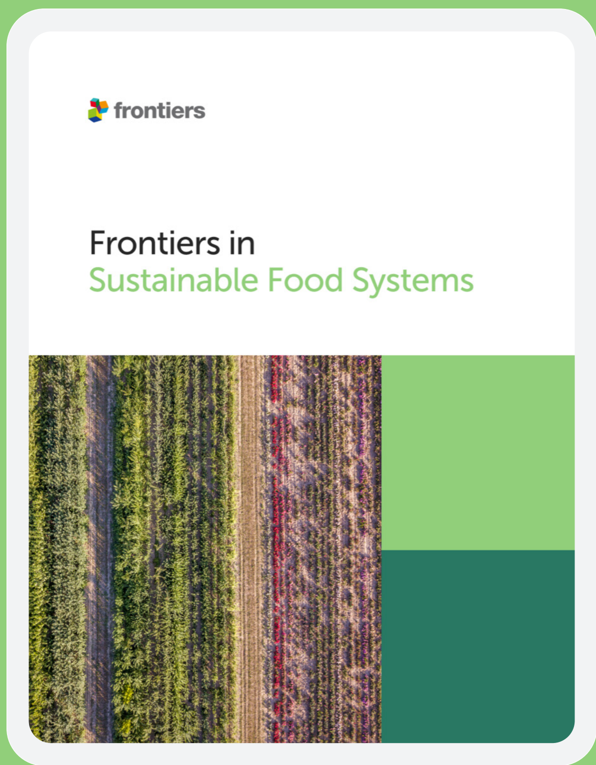
Frontiers in
Sustainable Food Systems

Exploring sustainable solutions to global food security

Aligned with the UN Sustainable Development Goals, this journal explores the intersection of food systems, science and practice of sustainability including its environmental, economic and social justice dimensions.

Discover the latest Research Topics

See more →



Frontiers

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

Contact us

+41 (0)21 510 17 00
frontiersin.org/about/contact