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How to achieve a planetary health diet through system and paradigm change?

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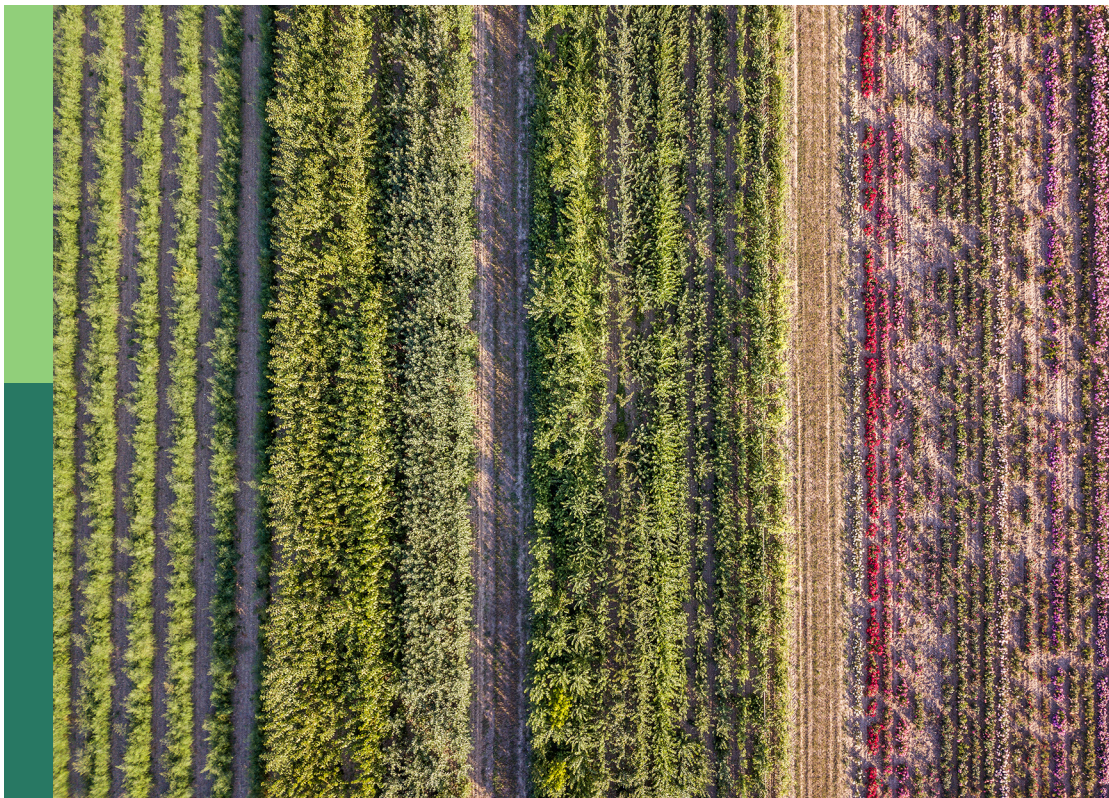

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How to achieve a planetary health diet through system and paradigm change?

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Table of contents

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Editorial: How to achieve a planetary health diet through system and paradigm change?

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Editorial on the Research Topic
How to achieve a planetary health diet through system and paradigm change?

A transition toward planetary health diets is urgent. Eating in ways that promote "planetary health" includes an increased intake of plant-based foods, such as legumes, nuts, grains, fruit and vegetables, and a reduction of meat and dairy, especially in the global North, in order to keep people and the planet "healthy" (Willett et al., 2019). Today's food systems are responsible for an unsustainably large amount of negative impacts, including obesity and under-nutrition, global greenhouse gas emissions, deterioration of natural resources, erosion of biodiversity, and the suffering of billions of livestock animals (Weis, 2013; Gilson and Kenehan, 2018; Swinburn et al., 2019; Almond et al., 2020; Bovenkerk and Keulartz, 2021; IPCC, 2022). Shifting toward plant-rich eating, especially in the global North, is often identified as essential for climate change mitigation and adaptation, for restoring damaged ecosystems, alleviating the sixth mass extinction of species, and creating a more just and resilient food system.

Exploring food-related consumer practices, behaviors and characteristics and the possibilities for new products, such as meat replacements, to help this transition has been the focus of significant research (e.g., Twine, 2018; Varela et al., 2022; Hansen et al., 2023). However, transforming current food systems toward sustainability is largely a political and power-related issue (Béné, 2022; Mylan et al., 2023). Our Research Topic draws attention to these dimensions of a planetary health-focused dietary transition.

We ask: What drivers—beyond individual practices—can generate system and paradigm-level change?

The incumbent actors and structures strongly resist necessary transformative changes but purposive change in food systems is also largely about discursive power (Fuchs et al., 2016), as well as about establishing and cultivating new values, norms, and paradigms, associated with the deeper, stronger leverage points for societal change (Meadows, 1999; Dorninger et al., 2020; see also Kaljonen and Lonkila, forthcoming; Northcott et al., 2023). Finally, it is about transformation in food systems governance (Béné, 2022).

The article collection in this Research Topic offers case studies and more global views, to identify through qualitative and quantitative analyses some key barriers to, and potential opportunities for, a sustainable food system transformation. The main proposals include a sharp focus on discourses, especially how to move beyond a polarization between animal-free and animal-centric food system paradigms; creating a level playing field for alternative protein industries, e.g., by shifting subsidies; exploring opportunities within alternative socioeconomic models of agriculture and new forms of human-animal relationships to bring about value and paradigm changes; building strong policy coalitions toward dietary change; and recognizing the feasibility of aligning food system transformation in terms of food security, land use, and global trade, as well as with sustainable development goals.

In her article, Bless uses the successful reduction of tobacco consumption in Australia to discuss a potential large-scale reduction of red meat consumption, within a national context where both tobacco and red meat have had strong cultural and economic significance. Bless explores policy actions along the *3Is framework* of "Ideas, Interests and Institutions", stressing the importance of addressing the discourse level—e.g., ideas, beliefs and paradigms—building unified and substantial policy coalitions to successfully break the inertia, challenge powerful vested interests and push for change, and allowing for enough time to bring about a transformation.

In Brazil, a country with a very powerful animal agriculture sector, Newton et al. identify opportunities for scaling up plant-based meats through policy measures. The authors use the Delphi method to explore what actions should be prioritized when resources are limited, considering importance, neglectedness, and tractability as key criteria. The experts' consensus is that lowering the price of plant-based meats and creating a level playing field for the alternatives industry should be prioritized. The authors recognized, however, that, in this context, one of the biggest challenges will be how to ensure meat replacement rather than (simply) the addition of alternatives to animal-based meat consumption.

In the next article, Bellamy et al. explore modes of dietary change that, if scaled up, could facilitate paradigm-level change. Using interviews and food diaries to compare the diets of people joining Community Supported Agriculture (CSA) schemes in the United Kingdom with those of the wider UK population, the authors show that, in line with prior studies, people joining a CSA scheme feel more empowered to change their diets toward a planetary health diet. Being involved with CSA schemes may also positively affect wellbeing and nature-related values. The authors discuss the policy implications of their findings, encouraging further research on the dynamics of joining CSA schemes vis-á-vis willingness to change diets.

Analyzing existing success stories of transitioning away from livestock farming, Salliou studies the voluntary *transfarmations* of 27 livestock farmers in Europe and the United States. These post-livestock farmers take two distinct transfarmation pathways. In the first, they set up farm animal sanctuaries, largely motivated by compassion. In the second, they remain in the agricultural sector but move to direct-to-consumer market gardening or mushroom production. Notably, the sanctuary model offers opportunities for the *care economy* (Lorek et al., 2023) whereby both animals and humans are cared for. Salliou argues that sanctuaries could become "incubators of new social arrangements between humans and non-human animals" (p. 8) and blueprints for a wider diffusion of a paradigm shift toward interspecies justice.

Investigating potential large-scale change, Schiavo et al. present a modeling exercise assessing the global impacts of a deep agroecological transition in the European Union including a 50% reduction in meat consumption. The analysis suggests that ensuring global food security, while maintaining existing EU farmlands is possible *as long as* EU diets become more plant-based. EU food export levels could also be maintained and food imports reduced, even if the rest of the world undergoes a similar transformation in agriculture and diets. In sum, a large-scale, system-level transformation is possible and can also be just, meeting the needs of both global South and North.

In another global analysis, Chen et al. offer a quantitative review of how global dietary change can align with relevant Sustainable Development Goals (SDGs). Comparing current diet patterns to the EAT-Lancet reference diet (Willett et al., 2019), dietary environmental footprints and the affordability of healthy diets are mapped for over 150 countries. In this process, geographic hotspots are identified and potential trade-offs in achievement of different SDGs highlighted. The authors emphasize that transformation-related policy challenges can only be solved by breaking disciplinary silos and bringing different actors and stakeholders together to drive the transformation.

Finally, Béné and Lundy propose a political economy and critical discourse analysis to explore the current debate around protein transition toward alternative, or *new meats* (Kanerva, 2021). Their analysis suggests that the polarization of the present discourses between the alternative protein proponents and the red meat supporters functions as a powerful barrier holding back progress toward the necessary transformation of the system. A concerning message emerging from the study is that powerful actors benefiting from the current red meat dominance might have already co-opted the transition process, in part by investing heavily in it, to ensure that they can have it both ways. The authors conclude, however, that managing the transformation successfully is possible since no principle conflict exists between transitioning to more plant-based diets in the global North while increasing meat consumption for vulnerable groups in the global South.

The road to transformation includes many hurdles, yet needs to be traveled fast. Although addressing the most difficult power-related questions remains challenging, this collection of articles identifies the importance of having a strategic approach to system change, especially in the context of power imbalances; addressing counterproductive discourses and mobilizing beneficial ones; building alliances; and using economic and social policies which hold potential to facilitate paradigm change.

Author contributions

MK: Writing – original draft, Writing – review & editing. SE: Writing – review & editing. CB: Writing – review & editing.

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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.

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Dietary Change and Global Sustainable Development Goals

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Food production for human consumption is a leading cause of environmental damage in the world and yet over two billion people suffer from malnutrition. Several studies have presented evidence that changes in dietary patterns across the world can lead to win-win outcomes for environmental and social sustainability and can complement ongoing technological and policy efforts to improve the efficiency of agricultural production. However, the existing evidence have been compiled in "silos" by a large range of researchers across several disciplines using different indicators. The aim of this quantitative review is to bring together the existing knowledge on heterogeneity of current dietary patterns across the world and how a transition toward healthy diets in different countries can aid in progress toward multiple global Sustainable Development Goals (SDGs). We first summarize the nutritional quality, economic cost, and environmental footprint of current diets of over 150 countries using multiple indicators. Next, we review which shifts in dietary patterns across different world regions can help toward achievement of SDG2 (Zero hunger), SDG3 (Good health and wellbeing), SDG 6 (Clean water and sanitation), SDG13 (Climate action), SDG14 (Life below water), and SDG15 (Life on land). Finally, we briefly discuss how to enable the shift toward sustainable dietary patterns and identify the research and data gaps that need to be filled through future efforts. Our analysis reveals that dietary change is necessary in all countries as each one has unique priorities and action items. For regions such as Sub-Saharan Africa and South Asia, increased intake of nutrient dense foods is needed to address deficiency of essential nutrients like folate, potassium, and vitamin A. For North America and Europe, shifting toward more plant-based diets would be healthier and simultaneously reduce the per capita environmental footprints. The results can be useful for policymakers in designing country-specific strategies for adoption of sustainable dietary behaviors and for food industry to ensure the supply of sustainable food items customized with regions' need.

Keywords: dietary change, environment, sustainable development goals (SDGs), climate-change, malnutrition

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INTRODUCTION

The United Nations Sustainable Development Goals (SDGs) outline the global consensus on social, economic, and environmental targets that humanity is striving to achieve by the year 2030 (United Nations, 2015). Achievement of these 17 SDGs is highly dependent upon the dietary habits of people across the world. This is because over two billion people suffer from malnutrition and dietary

factors are one of the main causes of premature mortality and morbidity according to global burden of disease assessment (GBD 2019 Diseases Injuries Collaborators, 2020), thereby hampering the progress toward SDG2 (Zero hunger) and SDG3 (Good health and wellbeing).

Moreover, current agricultural production sector supplying food for human consumption is the leading employer of the people and a main contributor to the environmental problems such as GHG emissions, freshwater scarcity, eutrophication, land degradation and biodiversity loss (Chaudhary et al., 2018a; Willett et al., 2019), thereby hampering the progress toward SDG 6 (Clean water and sanitation), SDG13 (Climate action), SDG14 (Life below water), and SDG15 (Life on land).

A global transition toward sustainable diets that are affordable, nutritionally adequate, and environmentally friendly will be key in achieving several SDGs simultaneously (Roberts and Mattoo, 2019; Garcia et al., 2020; Vågsholm et al., 2020). As of today, this seems a mammoth task because the current diets of most people around the world is either lacking in essential micronutrients, or high in nutrients of health concern or high in environmental footprint or all of the above (Springmann et al., 2018a).

Earlier literature in this field explored the health, nutrition, environment, or economic consequences of a shift from current toward alternative diets such as vegan, vegetarian, Mediterranean, etc. at the national or regional levels (Vanham et al., 2013). This was followed by several global scale studies that compared the intake levels of major food groups in different countries with alternative or WHO recommended levels and quantified the benefits of such a transition on health or environment (Tilman and Clark, 2014). All these studies were confined to a limited number of sustainability indicators such as GHG emissions, freshwater use, disease mortality, etc. (Jalava et al., 2014; Springmann et al., 2016).

This was followed by one of the most comprehensive analysis on this topic to date, where the recent EAT-Lancet commission on healthy diets from sustainable food systems proposed a healthy diet that meets the daily nutritional recommendations and does not transgress the different environmental planetary boundaries (Willett et al., 2019). Later studies calculated the cost of this healthy diet for different countries and reflected upon the economic sustainability or affordability dimension of healthy global diets (Hirvonen et al., 2019).

However, we realized that the published literature on dietary change to improve sustainability outcomes have been spread across a wide range of journals—each catering to a niche audience in silos (Jones et al., 2016). Studies discussing dietary change under a consistent framework of SDGs are almost non-existent. The aim of this study is to fill this research gap.

Here we perform a review to summarize the existing knowledge on how the dietary transformation across the world can help the progress toward multiple sustainable development goals (SDGs). We first summarize how the current diets of different countries look like from the social (nutrition), environmental, and economic dimensions of sustainability. For this, we review the nutritional quality, economic cost and environmental footprint of current national diets calculated by recent studies using several indicators. Next, we review the literature on how a shift in dietary patterns across different world regions can help achievement of SDG2 (Zero hunger), SDG3 (Good health and wellbeing), SDG 6 (Clean water and sanitation), SDG13 (Climate action), SDG14 (Life below water), and SDG15 (Life on land). Finally, we review studies on different policy or behavioral interventions that can help adoption of sustainable diets. We end the review by laying down the limitations of existing dietary sustainability studies and identify research or data gaps that need to be filled through future efforts.

SUSTAINABILITY STATUS OF CURRENT DIETS OF DIFFERENT WORLD REGIONS

Current Dietary Patterns Vis-à-Vis Dietary Recommendations

Early work on proposing the healthy eating principles and recommended intakes of different food groups were carried out by World Health Organization (WHO) (WHO, 2003, 2020; WHO and FAO, 2004) and other institutions (e.g., *Harvard's Healthy Eating Plate*) based on the link between food intake and the risk of undernutrition, premature mortality from diet-related non-communicable diseases (NCDs) and obesity. An increasing number of countries have since then established the national food-based dietary guidelines (FBDGs) that fit the country-specific food availability, dietary habits, and nutrition concerns (WHO, 1998).

However, it is possible that a healthy diet has huge environmental impacts and thus its supply would not be sustainable in long term. Reflecting this need to consider the global environmental targets such as planetary boundaries (Steffen et al., 2015) or those agreed upon by several countries in the Paris climate deal (United Nations Framework Convention on Climate Change (UNFCCC), 2015; Rockström et al., 2017), recent guidance on sustainable diets is also emphasizing the need to add environmental sustainability criteria in addition to the nutrition, thereby promoting foods that are not only nutrient dense but also low in their environmental footprints (Behrens et al., 2017; Blackstone et al., 2018; Ritchie et al., 2018; FAO and WHO, 2019; Herforth et al., 2019; Willett et al., 2019; Kesse-Guyot et al., 2020; Springmann et al., 2020).

The reference diet proposed by the EAT-Lancet commission is one such attempt as it considers the dietary risk factors, nutrient adequacy and five environmental planetary boundaries (Willett et al., 2019). Their reference diet provides the mean value along with a range for the intake amounts of 16 food groups. Other global studies have derived country-specific sustainable diets using mathematical optimization algorithms that meet the nutrition, environmental and cultural acceptability constraints (Chaudhary and Krishna, 2019). Certain authors have also derived optimal diets at the national level considering nutrition, environment as well as the economic cost of daily diet in local food market (Gephart et al., 2016; Perignon et al., 2019; Abejón et al., 2020; Eini-Zinab et al., 2020).

Apart from health, nutrition and environmental dimensions, there have been calls to further improve the national dietary guidelines taking into account additional factors such as

affordability of food items, subnational differences in food habits, cultural diversities, and income inequality alongside other indicators of food system sustainability to achieve more realistic and feasible dietary transformations (Chaudhary et al., 2018a; He et al., 2018; Batlle-Bayer et al., 2020; Blackstone and Conrad, 2020; Esteve-Llorens et al., 2020; Lassen et al., 2020; Moberg et al., 2020; Raghunathan et al., 2020; Sharma et al., 2020).

A comparison of the current intake of different food items or groups in different countries with the recommended intake levels proposed by dietary guidelines has revealed that a global average daily diet is low in fruits, non-starchy vegetables, legumes, nuts, and seeds, while high in red and processed meat, added sugar and roots and tubers (Afshin et al., 2019; Willett et al., 2019). **Figure 1** shows the geographic variability in diets across the world compiled by comparing the current intake levels of major food groups with their EAT-Lancet recommended levels.

The diet in the low-income regions like Sub-Saharan Africa is primarily composed of cereals, roots and tubers which contain mainly carbohydrates, while the diets in high-income countries source energy primarily from non-staple foods with high quantities of animal-based products (e.g., meat and dairy), sugar and fats (Chaudhary et al., 2018a; Chaudhary and Krishna, 2019; FAO et al., 2020).

Only 55% of the world population has average fruit and vegetable availability above the recommended level of 400 g capita-1 day-1 (Mason-D'Croz et al., 2019a; WHO, 2020). On average, the current global intake of fruits and vegetables is around 57% of the recommended amount and ranges from around 25% in several South Asian and Sub-Saharan African countries to around 95% in certain Mediterranean, Middle East and North African countries such as Armenia, Turkey, Tunisia, Romania, Egypt, and Iran (Afshin et al., 2019; Mason-D'Croz et al., 2019a; Willett et al., 2019; Springmann et al., 2020; **Figure 1**).

As one of the major plant-based protein sources, the reference diet from EAT-Lancet Commission report proposed an average 75 g per capita daily intake of dry beans, lentils, peas, and soy. Current legume consumption globally is remarkably insufficient compared to the recommended amount. For legume products, Sub-Saharan Africa, Latin America and Caribbean, and India have highest per capita consumption, while Europe and Central Asia has the lowest intake. The average daily consumption of roots and tubers is above the level in EAT-Lancet diet across all regions, with the highest intake in Sub-Saharan Africa and the lowest in South Asia. Current intakes of nuts and seeds are substantially below the recommended levels across all geographical regions (**Figure 1**).

Globally, the current livestock meat intake is higher than the recommended levels except in South Asia and Sub-Saharan Africa. For red meat, per capita average intake is highest in North America, followed by Europe and Central Asia, China, and Latin America and Caribbean. Mongolia, Argentina, Australia, Turkmenistan, and United States are the top consumers of ruminant meat (beef and lamb) with the highest per capita values. High-intake regions like North America have 15 times more per capita intake than low-intake regions like South Asia (**Figure 1**). North America also has the highest per capita consumption of dairy products, with around seven times the daily dairy intake of people in Sub-Saharan Africa and East Asia and Pacific. Europe and Central Asia has the second largest dairy intake.

Nutritional Quality of Current National Diets

SDG2 (zero hunger) and SDG3 (Good health and wellbeing) underscore the importance of the nutritional quality of diet for a healthy life. Apart from calories, human body needs several essential nutrients to support the body functions (Fern et al., 2015) including macronutrients such as protein, fiber and poly-unsaturated fatty acids (PUFA); minerals (iron, potassium, phosphorus, calcium, zinc, copper, magnesium, manganese, selenium) and many vitamins. The daily per capita recommended intake levels of essential nutrients for different age groups is available from agencies such as WHO or the U.S. Institute of Medicine (WHO, 2003; Institute of Medicine, 2005). Then there are nutrients of health concern such as saturated fats, sugar, sodium, cholesterol, whose intake above a certain level is associated with negative impacts on the body functioning (Fern et al., 2015).

Many studies have linked the nutrient density (amounts per gram) of individual food items with their daily per capita intake amounts to calculate the current intake levels of nutrients in different countries and compared it with the recommended intake levels (Chaudhary et al., 2018a; Springmann et al., 2018b; Chaudhary and Krishna, 2019). **Figure 2** shows the comparison of current and recommended intake levels of selected nutrients with high deficiency prevalence in different regions of the world.

Low intakes of dietary fiber, iron, potassium, vitamin A, folate, vitamin E, riboflavin (vitamin B2), vitamin B12, choline, and vitamin K are most prevalent globally (Beal et al., 2017; Springmann et al., 2018b; Chaudhary and Krishna, 2019).

The diets in the western countries are high in calories, low in several essential micronutrients and very high in nutrients of health concern (cholesterol, total fat, sugar, saturated fat). Diets in Africa and Asia are low in several essential micronutrients but also low in nutrients of health concern. A few countries in Sub-Saharan Africa here have diets low in calories as well.

The global average intake of the calories and the three essential macronutrients (protein, fiber, and polyunsaturated fatty acids) is much closer to their respective recommended levels compared with the intake of essential vitamins and minerals which is rarely adequate. Sub-Saharan Africa and India have the lowest average intake of protein while the intake in North America, Europe, China, and Latin America and Caribbean is way high and surpasses their mean population-level requirements. The intake of dietary fiber is most inadequate in South Asia and East Asia and Pacific. Across geographic regions, the intake of polyunsaturated fatty acids (PUFA) is most inadequate in South Asian countries, followed by Sub-Saharan Africa and East Asia and Pacific. United States and Israel have the highest national average PUFA intakes, twice the amount of their recommended levels.

Regarding vitamins, globally, the population-weighted average intakes are below their requirements for folate, riboflavin, choline, vitamin B12, vitamin K, vitamin E and vitamin A (Chaudhary and Krishna, 2019). The average folate

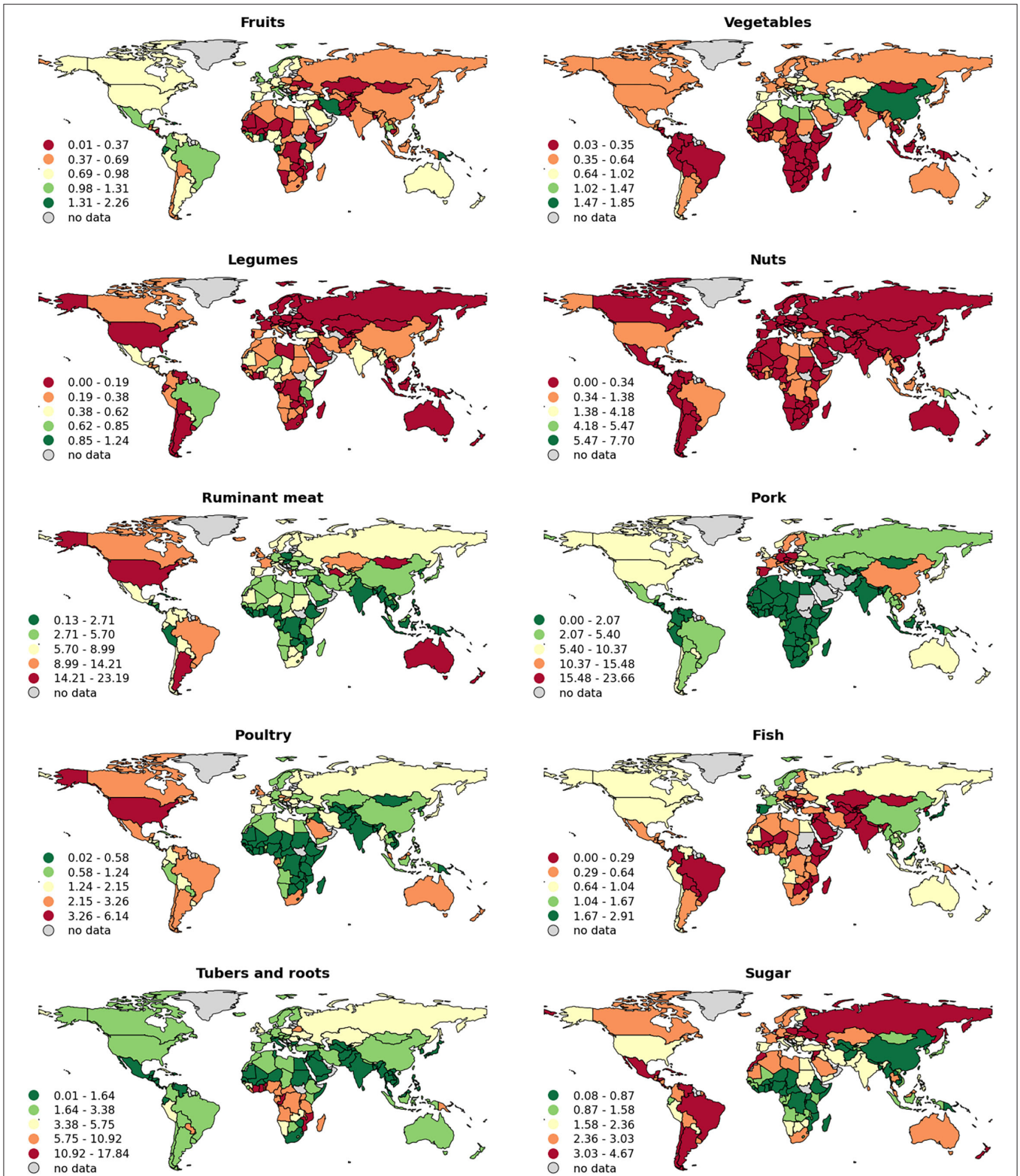

FIGURE 1 | Diets in different countries relative to the EAT-Lancet reference diet. Ratio of current to EAT-Lancet recommended intakes of different food groups per country are shown. We adopted the national average intake estimates (year 2010) from Willett et al. (2019), and the references proposed by EAT-Lancet Commission for the major food groups to calculate the ratios of current to reference intake levels. The darker red color indicates an insufficient intake of sustainable healthy foods or an excessive intake of unsustainable unhealthy foods in the national average diet.

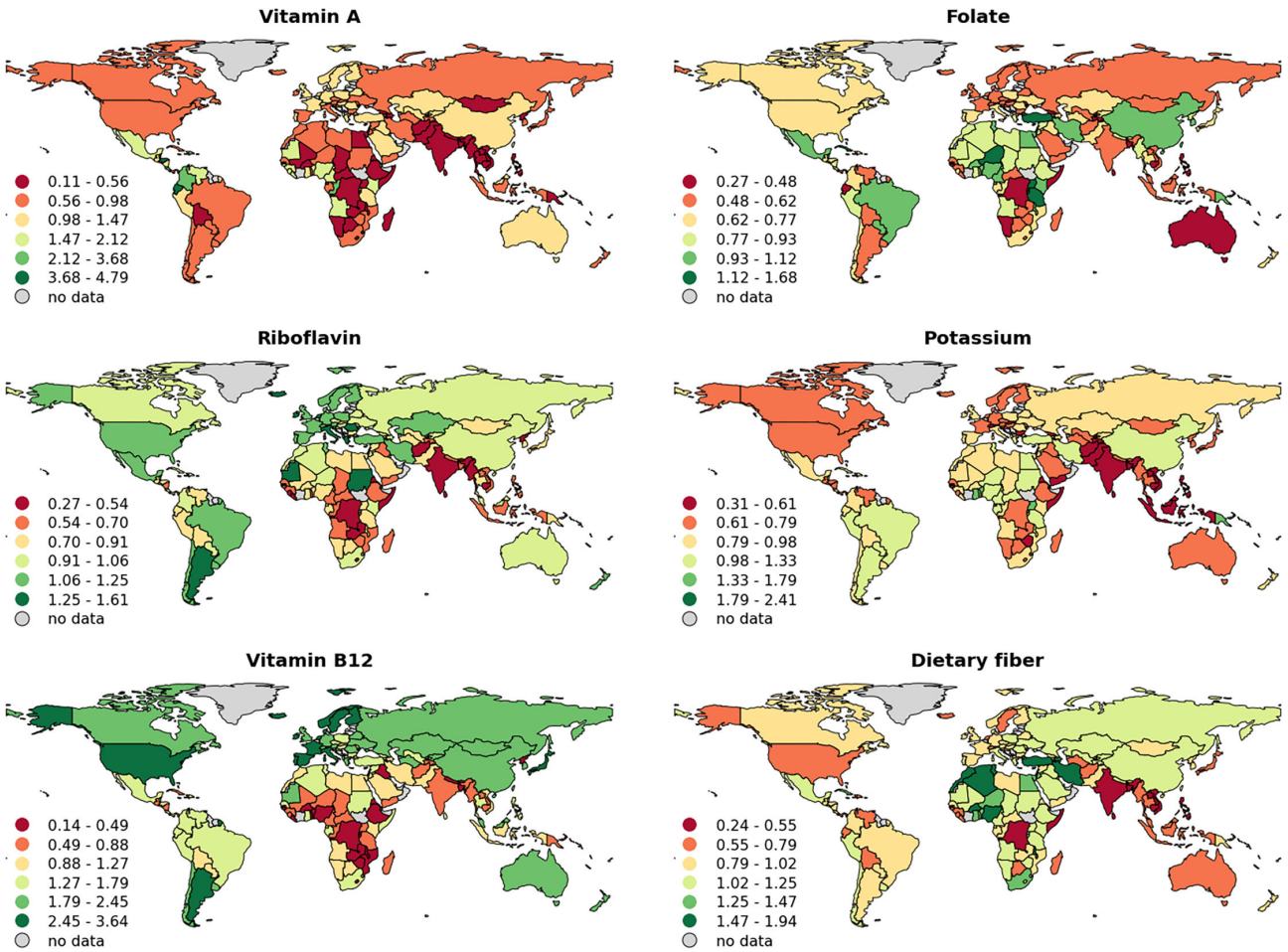

FIGURE 2 | Ratio of current dietary supply to recommended intake for selected nutrients. Recommendations are population level average Reference Nutrient Intake (RNI) per capita per nutrient for each country which are calculated following the methods in Chen et al. (2020). Current intake levels (year 2010) were adopted from Springmann et al. (2018b).

intake is inadequate (ratio < 1) across all regions except China. Rwanda, Cuba, and Burundi have the highest national dietary folate intake while Somalia, Guinea-Bissau, and Sri Lanka are estimated to be most inadequate in their folate intake (**Figure 2**). Riboflavin (or vitamin B2) in current diets is lower than the recommended amounts for India, South Asia, Sub-Saharan Africa, East Asia and Pacific, and Middle East and North Africa. Democratic Republic of the Congo, India, and Sri Lanka have the lowest riboflavin content in their national average diets, accounting for <40% of their required amounts (**Figure 2**).

The average vitamin A intake is inadequate in South Asia, India, East Asia and Pacific, Middle East and North Africa, and North America. Diets in South Asia and India contain the lowest vitamin A level and their dietary vitamin A only fulfill 40% of the daily requirement (**Figure 2**). Indian diets are also the most inadequate in vitamin B12 which is only found in animal-based foods, followed by diets in Sub-Saharan Africa and South Asia (**Figure 2**). The vitamin C requirements are met by current average diets of all regions except in South Asia. Diets in most world countries (86%) contain less Choline than the reference of 550 mg per capita per day, and people in South Asia and Sub-Saharan Africa have lowest intake level (Chaudhary and Krishna, 2019). Vitamin K in the average diet of Sub-Saharan Africa is the lowest, followed by South Asia and India, barely reaching two third of the required level (Chaudhary and Krishna, 2019). Vitamin E intake on average is inadequate in South Asia, India, Latin America and Caribbean, Sub-Saharan Africa, East Asia and Pacific, and China (Chaudhary and Krishna, 2019).

Regarding minerals, average intake of potassium is lower than the daily recommendation in nearly every region except China that just meets the level. Latin America and Caribbean and Sub-Saharan Africa have relatively higher potassium intakes than other regions. The estimates for year 2011 show that 90% of the global population who were at risk of calcium and zinc deficiency due to insufficient food supply lived in Africa and Asia (Kumssa et al., 2015). Dietary calcium is highest among North America and Europe and Central Asia, while lowest for countries in Sub-Saharan Africa and East Asia and Pacific where the current diets do not meet its recommended levels.

Regarding the intake of nutrients of health concern, the intake of saturated fatty acids exceeds the maximum allowable limit in North America, Europe and Central Asia, China, Latin America and Caribbean. The global consumption of sodium is far higher than the optimal level in many regions. China has the highest sodium intake of 10.7 g per capita per day, followed by East Asia and Pacific countries such as Singapore, Brunei Darussalam, and Japan (Afshin et al., 2019). The global average intake of sugar far exceeds the EAT-Lancet recommended level and the energy-dense and nutrient-poor food products like sugar-sweetened beverages are excessively consumed globally especially in North America and Latin America and Caribbean (Afshin et al., 2019).

Environmental Footprint of Current Diets

Food or feed production for ultimate human consumption causes massive environmental damage in the form of greenhouse gas emissions, eutrophication, water scarcity, land utilization, biodiversity loss etc., thereby hampering the achievement of multiple SDGs (Willett et al., 2019). Globally, food systems contribute to around one third of global GHG anthropogenic emissions from sources including land-use change (e.g., due to conversion of forests into farmland/pasture), the enteric fermentation of ruminants, fertilizer application, and energy use (Vermeulen et al., 2012; Crippa et al., 2021; Hong et al., 2021). Food production utilizes ∼40% of global ice-free land surface (Foley et al., 2011), which not only weakens the carbon sinks but also undermines the natural habitats of species and ecosystem intactness (Kastner et al., 2021).

Global food systems in 2010 are responsible for ∼5.2 billion tons of carbon dioxide equivalent direct GHG emissions (referring to methane and nitrous oxide), 12.6 million km^2 of cropland use, 1,810 km^3 freshwater use, 104 teragrams nitrogen and 18 teragrams phosphorus fertilizer application (Springmann et al., 2018a). Among these five environmental impact domains with quantitative planetary boundary estimates for global food systems (Springmann et al., 2018a; Chaudhary and Krishna, 2019), boundaries for GHG emission and nitrogen fertilizer use are more difficult to meet with around 40% of all countries having their average diet-related environmental footprints exceeding the planetary boundaries (Chaudhary and Krishna, 2021). The planetary boundaries reflect the maximum allowable environmental emissions/limits, transgression of which would increase the risk of Earth system at risk of unwanted outcomes due to ecosystem destabilization, jeopardizing human livelihood including the food systems (Steffen et al., 2015).

Figure 3 shows the heterogeneity of environmental impacts linked with the average daily per capita diets of different countries. Sub-Saharan Africa has the lowest per capita food-related environmental impacts on average (**Figure 3**). Regarding food-related carbon footprints, most regional average diets are above or near the planetary boundary except Middle East and North Africa, and India. Latin America and Caribbean has the largest carbon footprints embedded in their average dietary pattern. Per capita current diets in Uruguay, Montenegro, New Zealand, Serbia, and Australia are associated with the highest food-production related carbon footprints (>11 kg CO2 eq. per capita) (Springmann et al., 2020) which might be related to the consumption of food products such as high-emission ruminant meat (Poore and Nemecek, 2018).

Regarding nitrogen and phosphorus fertilizer application, the environmental footprints of national average diet are largest in China, followed by North America (Springmann et al., 2020). The associated impacts are driven by the inefficient fertilizer use and manure management related to the production of staples and livestock products.

Regarding cropland, Europe and Central Asia has the highest footprint per capita, followed by Sub-Saharan Africa and North America. Per capita cropland footprints are high for countries such as Niger, Kazakhstan, Australia, Russian, and Tunisia that source foods from low-yield crops and animals that rely on large amounts of crop feeds (**Figure 3**). The extensive grazing land demand for livestock-sourced foods contribute to high diet-related land footprints of countries such as Mongolia and Namibia (Chaudhary et al., 2018a).

Regarding freshwater, diets are associated with the highest footprints in South Asia, Middle East and North Africa, and India (**Figure 3**) where the water use is not efficient especially for products like rice, legumes, and nuts.

Compared to carbon, land, water, and fertilizer use, the impact of national food consumption on biodiversity has been less often assessed in the previous studies. The encroachment of species' natural habitat due to agricultural land use and the pollution from nutrient runoffs into water bodies greatly undermines the terrestrial and aquatic biodiversity of the region and threatens the species with extinction risk. The EAT-Lancet report estimated that the current agriculture driven biodiversity loss rate has already violated the planetary boundary of species extinction rate (Willett et al., 2019).

Other studies have calculated the food production, consumption and trade related national biodiversity footprints and found that high diet-related biodiversity footprint countries are either the ones that have high species richness density, natural habitat conversion and small share of imported food products (such as tropical Central America and Caribbean countries), or the regions with large per capita food consumption (such as North America and European Union) and high dependence on products imported from tropical biodiversity hotspots (Lenzen et al., 2012; Chaudhary and Brooks, 2017; Chaudhary et al., 2018a; Estrada et al., 2019).

Exports from Indonesia, Thailand, India, Australia, and Malaysia embody high biodiversity losses, meanwhile countries such as United States, China, Japan, and Germany imported large quantities of products that threaten the species in the country of production (Chaudhary and Kastner, 2016). Staple crops, sugarcane, palm oil, coconut, and cassava are responsible for the most global cropland use induced biodiversity impact, especially those produced in Southeast Asia (Chaudhary and Kastner, 2016).

Economic Cost of Current Diets

The local food market price is a key determiner of the dietary choices, especially for poor people with a limited income. The affordability of healthy food items for people with low socioeconomic status is important to ensure food security and

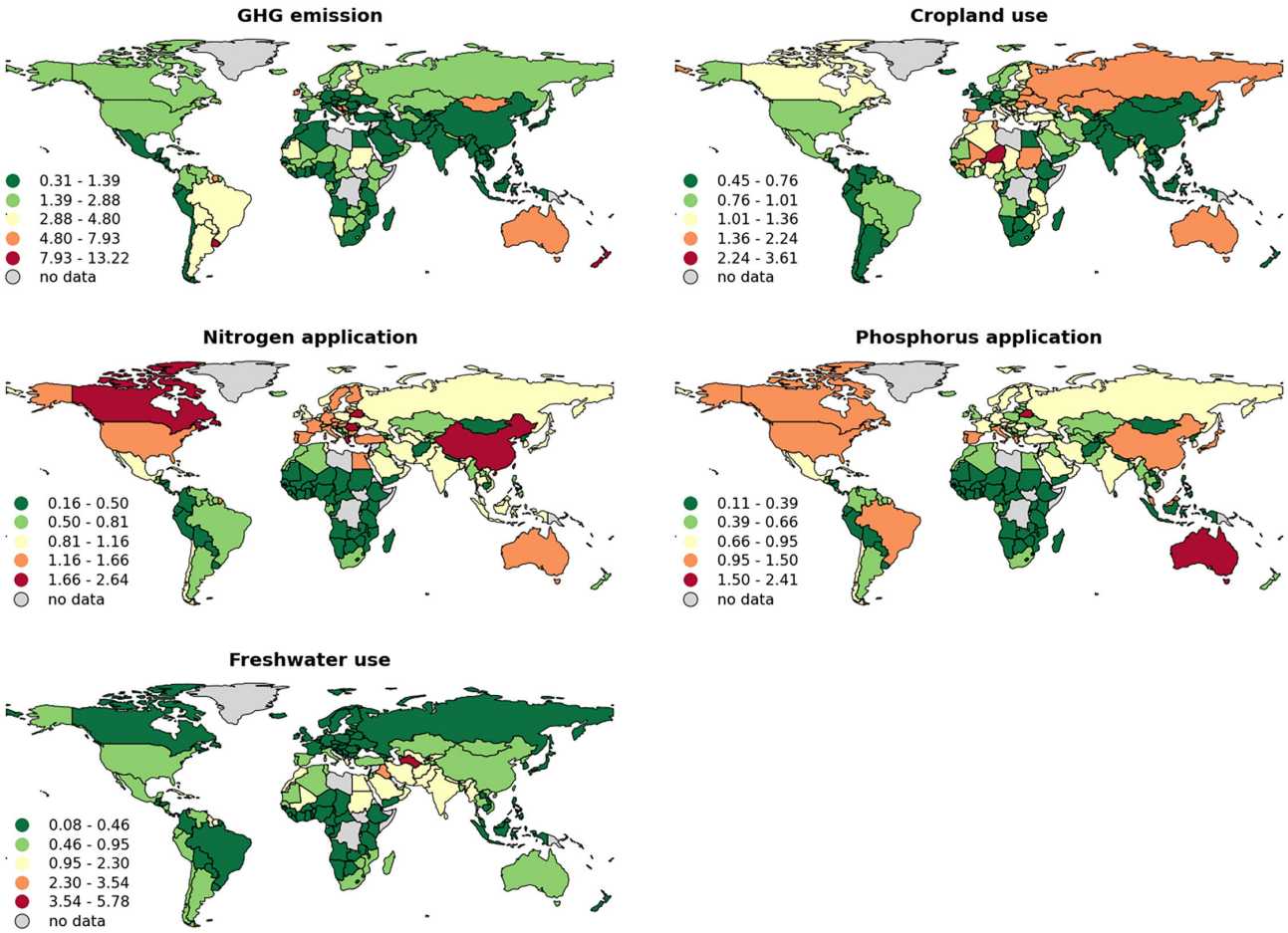

FIGURE 3 | Ratio of the per capita environmental footprints associated with current diets to food-related planetary boundaries. Environmental footprints regarding greenhouse-gas (GHG) emissions, cropland use, freshwater demand, nitrogen, and phosphorus application of national food consumption in year 2010 were estimated by Springmann et al. (2020). Per capita food-related planetary boundaries of global average were based on the estimates of Chaudhary and Krishna (2019) and Springmann et al. (2018a).

nutritional health (Darmon and Drewnowski, 2015). The price of foods and the income per household member often together determine whether people have economic access to the food that meet their nutritional needs and dietary preferences. For example, the low intake of fruit and vegetables in low-income countries was found to be associated with their high relative cost in the market (Miller et al., 2016).

To estimate the dietary cost, earlier studies sourced food price or consumer expenditure data from national statistical agencies, retailer records or consumer survey (Wilson et al., 2013; Donati et al., 2016; Chen et al., 2019; Reynolds et al., 2019). More recent global-level studies adopted the nationally representative retail prices of 680 standard food products across 170 countries from the World Bank's International Comparison Program (ICP) (Headey and Alderman, 2019; Hirvonen et al., 2019; Herforth et al., 2020). Using this dataset, United Nations Food and Agriculture Organization recently found that the diets satisfying the daily caloric requirements through cheapest available staple foods are affordable for almost all people in most countries except Sub-Saharan Africa where 15% of population cannot afford even this calorie sufficient diet (**Figure 4**).

However, a nutrient adequate daily diet is rather expensive for many regions as over 60% of population in Sub-Saharan African and 12–21% of people living in Latin America and Caribbean, South Asia, East Asia and Pacific, and Middle East and North Africa cannot afford the least-cost diets which are adequate in terms of 23 macro- and micronutrients (**Figure 4**). Countries like Sudan, Madagascar, and Liberia would encounter the greatest affordability barrier where more than 85% of national population is unable to afford the food products for fulfilling their daily nutritional requirements (**Figure 4**).

Achieving the culturally favored healthy diets which follow the national dietary guidelines is even more challenging. Three billion people globally cannot afford such a diet. These recommended diets are often 60% more costly than diets that fulfill the nutritional adequacy and have nearly five times the cost of diets that just provide sufficient calories with cheap starchy staple foods (**Figure 4**; Herforth et al., 2020). These healthy diets

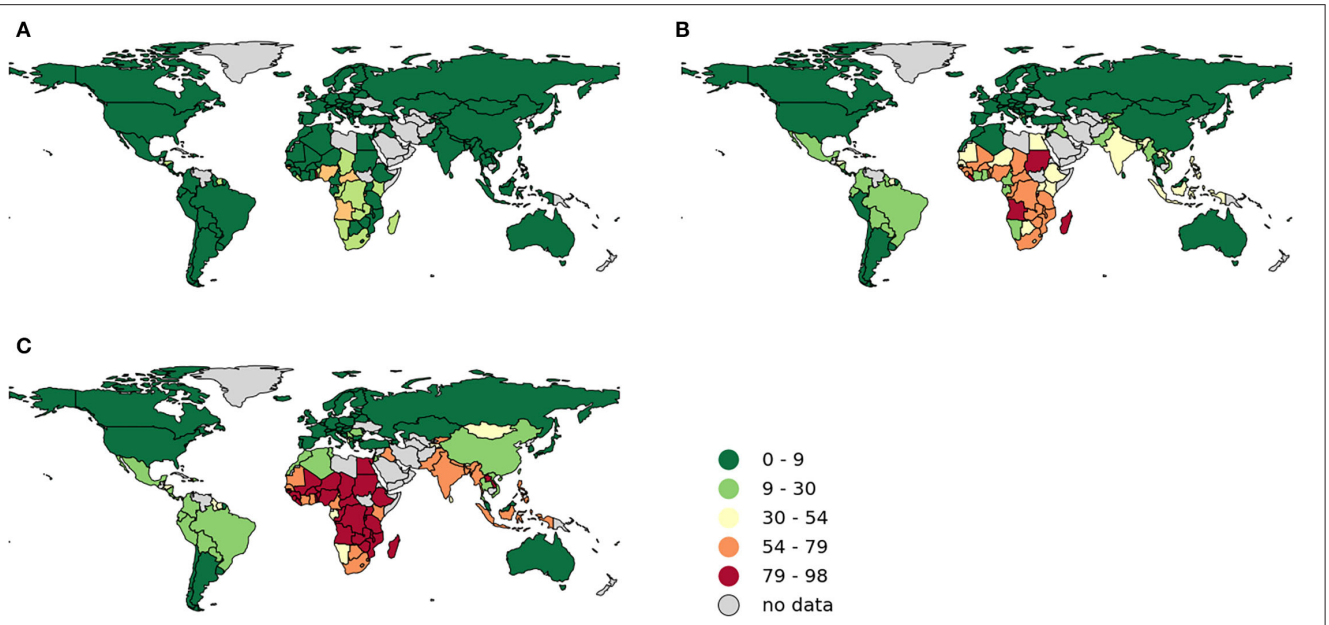

FIGURE 4 | Affordability of **(A)** energy sufficient diet, **(B)** nutrient sufficient diet, and **(C)** healthy diets. Higher values (in red) indicate the food is too expensive and not affordable to local population. The affordability is measured by the percentage of people in each country whose household income cannot afford the cost of the cheapest diets using locally available items, assuming they can spend no more than 63% of their income on food. For a given country, energy sufficient diet provides enough calories and is based on the least-cost staple foods, nutrient sufficient diet provides not only sufficient calories but also adequate amounts of essential nutrients, and healthy diets meet the national food-based dietary guidelines (FBDGs). Values were obtained from Herforth et al. (2020).

are unaffordable for almost 60% of people in South Asia and sub-Saharan Africa, over 45% of people in South-east Asia and over 20% of population in Latin America (**Figure 4**). In contrast, the cost of healthy diets account for a small fraction of per capita household income in high income regions such as Europe and Central Asia and North America where just 1–3% of people cannot afford it (**Figure 4**).

The high economic cost not only creates the barrier for the healthy eating but also hinders the possibility of meeting food related environmental sustainability targets. For example, the reference diet proposed by EAT-Lancet Commission which accounts for both human health and environmental sustainability, is found to be not affordable in many countries. For low-income countries, the mean daily cost of an EAT-Lancet reference diet is estimated to be $2.43 (in 2011 international dollars) accounting for around 89% of the average daily household income per capita (Hirvonen et al., 2019). The cost of such diets would account for the smallest fraction (4.4.%) of average per capita household income for people in North America and the largest portion (73%) for people living in sub-Saharan Africa (Hirvonen et al., 2019). Across food groups, fruits, and vegetables together account for the largest share of dietary cost on average globally. The share of animal sourced foods (i.e., meat, fish, eggs, and dairy) in total cost is highest in low-income countries at 33%.

Risks of unaffordability in terms of having a healthy diet are distributed unevenly among subgroups with socio-economic discrepancy. Even in affluent regions like the European urban area, the low-income households would have financial difficulties accessing the healthy diets complied the national dietary guidelines (Penne and Goedemé, 2020). The case study on dietary changes in India shows that approximately two-thirds of the rural Indian population could not afford a recommended healthy diet in 2011, despite the rapid average income growth in the past two decades (Raghunathan et al., 2020). High price of nutrient dense food items creates the financial barrier to shifting toward recommended healthy dietary pattern. People would need to spend an additional 2.4 US dollars for a diet that in line with the EAT-Lancet references in India, primarily to incorporate increased fruits and dairy products in daily diets (Gupta et al., 2021).

Besides the consumer's food purchase ability, another indicator, the Food Affordability Index considers the vulnerability to the food price shocks into the affordability assessment, indicating that Venezuela, Syria, Madagascar and sub-Saharan countries were most vulnerable to the supply of healthy foods and had the lowest food affordability in 2019 (The Economic Intelligence Unit, 2020).

For many regions and subpopulations, the current cost of healthy diets and nutritious foods is too high in comparison to the household income levels. The unaffordability could be a significant barrier for adopting the healthier and more sustainable diets unless sectors across food systems (e.g., production, trade, and market resilience) can facilitate the supply of the healthy foods such as vegetables, fruits, nuts, and dairy at lower prices (Hirvonen et al., 2019; Bai et al., 2020). For example, most of the cost of healthy diets can be attributed to two types of foods: protein-rich foods and fruits and vegetables accounting

for 44 and 40% of the total cost, respectively (Herforth et al., 2020). Financial interventions that target the source of the issue of unaffordability of healthy food items in a country and reduce the price barriers to access of these food commodities could help improve the economic access to healthy diets, especially for the low income and vulnerable population like children and the elderly (Rao et al., 2013; Hirvonen et al., 2019; Vandevijvere et al., 2020).

DIETARY CHANGE AND SUSTAINABLE DEVELOPMENT GOALS (SDGS)

Dietary Change and SDG2—Zero Hunger

The SDG 2 aims to end hunger and food insecurity (target 2.1) and all forms of malnutrition (target 2.2) by 2030. This means that not only can people have enough dietary calorie intake but also the essential nutrients like protein, fiber, unsaturated fatty acids, vitamins, and minerals. According to the estimates of year 2019, 690 million people global still suffer from hunger meaning their daily diets do not provide sufficient calories. Over two billion people (26% of the global population) suffer from malnutrition meaning that they do not have enough safe, sufficient and nutritious food available (FAO et al., 2020). The number of hungry people has been slowly rising since 2014 despite worldwide commitment and economic progress. The world is not on track to achieve the global nutrition and SDG 2 targets by 2030 if the trends of the last 10 years continue. Today's food systems still face the challenge from the burden of malnutrition shown in forms of undernutrition, micronutrient deficiency, and overnutrition (Popkin et al., 2020). It is clear that dietary change is needed in each country to achieve progress toward global sustainable development goals (SDGs).

Several global and regional studies have presented the required increase or decrease in the intake of individual food items or food groups necessary to achieve the daily nutritional needs for different countries. This includes the EAT-Lancet commissions' report and other studies that have employed optimization algorithm to derive a sustainable diet fulfilling daily nutritional requirements of all essential nutrients (Chaudhary and Krishna, 2019, 2021). They found that the malnutrition reduction effects from adopting healthier diets would entail different strategies and pathways.

For undernourished regions like sub-Saharan Africa and South Asia, the dietary shifts toward an increase in dietary energy and increased intake of almost all food items but especially nutrient dense animal-based products and fruits and vegetables would decrease the prevalence of hunger, undernutrition, and deficiency in essential nutrients. Replacing cereals and root products with diverse non-staple foods could reduce the risk of dietary nutrient deficiencies in Africa for micronutrients such as calcium, zinc, selenium, and iron that are associated with 20–50% inadequate intake among population currently (Joy et al., 2014; Gregory et al., 2017). A moderate intake of nutrient-rich fish or livestock products that are produced respecting the local environmental boundaries would help tackle the hidden hunger issue in undernourished regions (Beal et al., 2017; Chaudhary and Krishna, 2019). For example, the nutrient gaps (deficiency risk >20%) of calcium, iron, zinc, and vitamin A among coastal population in countries like Namibia, Mauritania and Kiribati could be resolved by the fish products (Hicks et al., 2019). To address the iron deficiency and associated anemia, a diet with iron-rich and nutrient-dense foods like lentils, pulses (Chaudhary et al., 2018b; Chaudhary and Tremorin, 2020) or animal-sourced foods is important to ensure the dietary quality and alleviate adverse health outcomes for children and women (Black et al., 2008). Although caution must be exercised as concerns have been reported by some studies on the low iron bioavailability of plant-sourced foods (Haider et al., 2018). Note that increased intake of food in the undernourished regions is likely to increase their environmental footprint as well as expenditure on daily diets (Chaudhary and Krishna, 2021).

For regions with widely sufficient food calorie intakes such as North America, Europe, and Australasia, malnutrition in the form of obesity and diet-related non-communicable disease prevalence have become an increasing concern (Cooper et al., 2019; Swinburn et al., 2019; Hawkes et al., 2020). Here the benefits would result from a restrain of excessive calorie and unhealthy nutrients such as added sugar and saturated fats that are consumed through discretionary products (Hadjikakou, 2017). An increased intake of fruits and vegetables (e.g., 250 g per capita per day more in North America), legumes, and roots, and a substantial reduction in meat, dairy, and eggs are expected to ensure the nutritional and environmental targets are met (Chaudhary and Krishna, 2019).

Adopting an energy-balance and nutrient-adequate diet are crucial to address the increasing coexistence of undernutrition and overnutrition (overweight and obesity) for countries undergoing rapid income growth and food environment transition such as Indonesia and many other Asian and sub-Saharan African countries (Popkin et al., 2020).

It is therefore important that governments pursue SDG2 without ignoring environmental impacts in order to avoid the potential trade-offs between global hunger (as well as "hidden hunger") eradication and environment-related SDGs (e.g., climate action, preserving life on land and water). Dietary change is often proposed as one indispensable strategy for feeding the projected future population (SDG 2) and achieving the climate change target (e.g., 1.5°C increase limit) simultaneously (Bajželj et al., 2014; Chaudhary et al., 2018a; Clark et al., 2020). Ensuring the availability of culturally-acceptable, low-cost, nutrient dense and low environmental footprint food items is the major challenge ahead for countries in timely achievement of SDG2.

Dietary Change and SDG3—Good Health and Wellbeing

Poor dietary quality is closely associated with the global burden of non-communicable diseases (NCDs) such as cardiovascular diseases, type 2 diabetes, and neoplasms. Globally, 11 million deaths and 255 million disability-adjusted life years (DALYs) were attributable to dietary risk factors including high intake of sodium, low intake of whole grains and fruits (Afshin et al., 2019).

TABLE 1 | Region-specific changes (%) in multiple indicators of sustainability resulting from a transition toward the EAT-Lancet reference diet.

Regions*	Environment**					Health	Nutrition	Economic
	GHG	Land	N	P	Water	Mortality	NBS	Cost
EAP	−4	+22	−8	+18	−1	−17	+12	+69
EUCA	−60	−15	−24	−24	+11	−25	+2	+65
LAC	−64	+1	−16	−13	−5	−24	+3	+53
MENA	−21	+1	−17	−11	+9	−24	+4	+61
NAM	−73	−24	−38	−38	−4	−23	+4	+26
SA	+22	+49	+27	+38	+31	−20	+17	+67
SSA	+20	+46	+32	+46	+63	−10	+6	+44
China	−47	+6	−13	−7	−16	−20	+1	+69
India	+3	+32	−9	+1	−14	−21	+13	+67

**Regions included: East Asia and Pacific (EAP), Europe and Central Asia (EUCA), Latin America and Caribbean (LAC), Middle East and North Africa (MENA), North America (NAM), South Asia (SA), Sub-Saharan Africa (SSA), China, and India.*

***Indicators included: environmental footprints regarding food-related greenhouse gas emissions (GHG), cropland use (Land), nitrogen application (N), phosphorus application (P), and freshwater use (water); premature mortality (Mortality); Nutrient Balance Score (NBS) which reflects the density of 19 healthy nutrients; economic cost of daily diets.*

Values in the table are the population-weighted regional average changes calculated from national values of indicators on environment impact (Springmann et al., 2020), health impact (Springmann et al., 2020), and nutrition quality (Springmann et al., 2018b).

For economic impact, values are the changes in median cost by a shift from nutrient adequate diet to the EAT-Lancet reference diet composed of the locally available and least-cost foods in each region. Data were obtained from Hirvonen et al., 2019.

Red shadowed values show an adverse impact such as the increased food-related environmental footprints and daily food costs.

Improving diets can help achieve the SDG 3 that nourish healthy lives. A growing number of studies have revealed the association between the reduced disease risks and the optimal intakes of whole grains, fruits, vegetables, legumes, nuts and seeds, red and processed meat consumption through indicators such as mortality and DALYs (Afshin et al., 2014; Li et al., 2014; Tilman and Clark, 2014; Wang et al., 2014, 2019; Aune et al., 2016; Mayhew et al., 2016; Springmann et al., 2016; Milner et al., 2017; Miller et al., 2020). Studies also found that the adherence to an alternative dietary pattern such as Mediterranean and Vegetarian diets is associated a lower risk of multiple chronic diseases (Orlich et al., 2013; Satija et al., 2016; Dinu et al., 2018). These evidence highlights the potential health benefits from shifting to an energy-balanced diet containing larger portions of plant-based and less-processed food products.

If the global population shifted from current diets toward the dietary pattern that EAT-Lancet Commission proposed, 10–12 million premature deaths due to NCDs could be prevented annually, meaning a 19–24% premature mortality reduction (**Table 1**; Willett et al., 2019). The mortality reduction from the recommended dietary shifts is projected to be distributed relatively evenly across regions, with slightly larger benefits in Europe and Central Asia, Middle East and North Africa, Latin America and Caribbean, and upper-middle-income countries (Springmann et al., 2018b).

For regions whose current diets are composed of abundant unhealthy foods, adopting the diets that are lower in the meat amounts and filling the gaps for fruits, vegetables, legumes, and nuts (e.g., EAT-Lancet, vegan, vegetarian, pescatarian diets) is projected to bring great population health benefits, with a 23–8% reduction in premature mortality in Europe and Central Asia, North America, Latin and Caribbean, and Middle East and North Africa. Such health benefit estimates are in alignment with the SDG 3 target 3.4 which aims to reduce one third of premature mortality from NCDs through prevention and treatment by 2030 (United Nations, 2021). Shifting to the diets that follow the national food-based dietary guidelines would lead to a reduction in premature mortality from diet-related NCDs as well but with smaller effects comparing to the extensive plant-based options (Springmann et al., 2020).

Indicators that monitor the progress for SDG 2 are also relevant for the mortality rate of maternal, neonatal and children under five (SDG 3). Maternal undernutrition contributes to fetal growth restriction thus increasing the risk of neonatal deaths. Maternal and child undernutrition is attributed to 35% of child deaths and more than 10% of total global disease burden (Black et al., 2008). Ensuring nutrient-adequate and balanced food intake is one of the crucial interventions for lowering disease risks and support children to reach their development potential.

In less-affluent regions such as sub-Sahara Africa and South Asia, shifting from current staple-based dietary patterns toward diets composed of a variety of nutritious food products could improve the energy balance and nutrient adequacy, leading to a reduction in undernutrition-related mortality.

Previous assessments of dietary changes often considered the long-term disease consequences for adults aged 20 year or older (e.g., the reduced premature mortality attributed to cardiovascular diseases) (Springmann et al., 2018b), however, did not explicitly address the burden mitigation effect related to macronutrient and micronutrient deficiency for vulnerable groups such as maternal and children under 5 years old (Gödecke et al., 2018; Willett et al., 2019; Zagmutt et al., 2020). Such effect interconnects with SDG 2 agenda and would have important contribution to the missions of SDG 3 especially for regions with large insufficiency in healthy foods and nutrient consumption.

Dietary Change and SDG 6—Clean Water and Sanitation

A recent review provides a critical examination of SDG 6 and its indicators (Germann and Langergraber, 2022). Current food systems are the largest consumer of global freshwater resources and to achieve the water scarcity reduction (target 6.4 of the SDG 6), there is need to improve their water use efficiency. A transition toward diets composed of foods that demand less water for production could help reduce freshwater use stress and avoid violating the environmental flow requirements for healthy aquatic ecosystems (Jägermeyr, 2020).

Lowering the fertilizer footprints through dietary shifts could also contribute to the achievement of SDG 6 (e.g., target 6.3), because the nutrient runoffs from fertilizer application in agricultural farms is among the leading polluters of rivers and lakes that jeopardizes the supply of safe drinking water. This impact will be discussed in the section on SDG 14 "life below water" as the nutrient pollution effect is linked with biodiversity agenda as well. In this section we will focus on the water scarcity reduction target within SDG 6.

Earlier studies at the continental scale have reported substantially high food-related water footprint reduction (by 20% or more) through a shift toward healthy plant-based options mainly attributed to a large decrease in water-intensive meat products (Vanham et al., 2013; Aleksandrowicz et al., 2016). Water footprints of red meat and farmed fish are on average higher than plant-based substitutes (Mekonnen and Hoekstra, 2011).

However, global assessments like Jalava et al. (2014) have illustrated the limited water saving effect of shifting to healthier diets. A decline of 1% in global freshwater footprint (or blue water footprint) was observed when shifting from conventional diets to the WHO's recommendations on macronutrients, sugar, fruits, and vegetables (WHO, 2003) at the global level. Recent study also showed a modest effect on freshwater use reduction if global population shift toward the EAT-Lancet Commission recommended reference diet, with 1-9% lesser water demand (Willett et al., 2019). According to their model, the reduction in water demand for animal products and feed crops was compromised by the increased demand for healthy foods like nuts, fruits and vegetables, which are relatively water-intensive (Willett et al., 2019). The dietary change effects on freshwater use would vary across regions. For undernourished regions like Sub-Saharan Africa and South Asia, improving dietary quality would be associated with more irrigation water use through increased intake of foods such as fruits, vegetables, nuts, legumes, animal protein (Willett et al., 2019).

In this case, solutions that improve water-use efficiency of food systems are needed (Davis et al., 2016; Rosa et al., 2018; Vanham and Mekonnen, 2021) along with identification of items within each food group that have relatively lower water use than the other items. For example, pistachios and almonds would not be the sustainable options for filling the intake gaps of nuts due to their high water footprints at 7,602 and 3,816 m^3/ton, respectively. In contrast, nuts with much lower freshwater demand like Kola nuts (26 m^3/ton) and chestnuts (174 m^3/ton) (Mekonnen and Hoekstra, 2011) might be better alternatives to meet daily recommended nuts intake amounts. Within animal-sourced foods, the low-food chain animal products such as bivalve mollusks, forage fish, and insects are associated with relatively low freshwater footprint and thus can act as sustainable alternatives to high food chain and high impact meat products such as beef or pork (Jalava et al., 2014; Kim et al., 2019).

Another issue is the origin of crop production as the water use for a particular crop and water scarcity varies widely across the globe. The freshwater footprint of rice production in Pakistan and Iran are highest among the rice producer countries, and one-kilogram of rice produced in India requires more freshwater than rice in other major producers like China, Indonesia, and Bangladesh (Kim et al., 2019). Dietary shifts from water-intensive rice toward more water-efficient whole grain choices like maize, millet, and sorghum could help India in progress toward SDG 6 by mitigating the existing water scarcity while satisfying the national nutrient intakes (Davis et al., 2018; Chaudhary and Krishna, 2021). The unsustainable water use driven by food trade is severe where the regional freshwater resources mismatch their production scale, thus call for more efficient trade to sustain the environmental flows (Dalin et al., 2014; Pastor et al., 2019; Rosa et al., 2019).

Other have demonstrated that a substantial fraction of fruits and vegetables imports of high-income temperate countries come from climate vulnerable and water scarce low-income countries (Scheelbeek et al., 2020). Here expansion of horticulture locally through novel agricultural systems in temperate water-abundant countries and dietary shifts toward more locally grown crops with lesser water use impacts and trade agreements with producer countries that seek to improve the water use efficiency of imported crops through technology transfer or other means can help progress toward SDG 6.

Dietary Change and SDG13—Climate Action

SDG 13 calls for urgent actions to combat climate change and the associated consequences. Growing number of studies have assessed the measures for cutting the greenhouse gas (GHG) emissions associated with food systems. Dietary change is an imperative measure for climate mitigation without sacrificing other sustainability domains (e.g., food security, biodiversity intactness) (Bajželj et al., 2014) as for most of world regions, GHG emissions associated with current per capita diet have transgressed the food-related carbon planetary boundary (**Figure 3**).

Diets with increasing replacement of emission-intensive foods with plant-based foods would be associated with a decrease in food related GHG emissions and can help in the achievement of SDG 13 and the commitments under Paris Agreement. As shown in **Table 2**, animal-sourced products in general have higher GHG emissions regardless of the unit used such as per weight, per serving, per calories, or per protein content among alternative food groups (Clune et al., 2017; Poore and Nemecek, 2018; Clark et al., 2019; Willett et al., 2019) and the ruminant

TABLE 2 | GHG emissions associated with major food groups.

Food group	GHG emissions (kg CO_2 eq per kg)	Products included
Beef and lamb	57.50	Beef (beef herd), beef (dairy herd), lamb and mutton
Fish	20.25	Fish (farmed), prawns (farmed)
Pork	12.31	Pig meat
Poultry	9.87	Poultry meat
Eggs	4.67	Eggs
Milk	3.15	Milk
Sugar	2.51	Cane sugar, beet sugar
Grains	2.28	Wheat, rye, rice, maize, oatmeal, barley
Nuts and seeds	1.83	Nuts, groundnuts
Legumes	1.39	Peas, other pulses
Vegetables	0.91	Brassicas, tomatoes, onions and leeks, other vegetables
Fruit	0.85	Apples, bananas, berries and grapes, citrus fruit, other fruit
Roots	0.74	Potatoes, cassava, root vegetables

Data are sourced from Poore and Nemecek (2018).

meats in particular have emissions more than 20 folds larger than plant-based products per unit calories (Clark et al., 2019).

A median of 22% GHG emission reduction effect was reported across various meat substituted diets including Mediterranean pescatarian, vegetarian, and vegan diets and up to 80% reduction could be achieved by plant-based diets (Hallström et al., 2015; Aleksandrowicz et al., 2016; Springmann et al., 2018a; Broekema et al., 2020; Drew et al., 2020). Transition toward healthy diets in high income and food secure regions has also been shown to massively reduce their environmental footprint, thereby compensating for increased environmental footprint due to transition of regions with high hunger prevalence toward a nutritionally adequate diet (Hasegawa et al., 2018; Willett et al., 2019).

Efforts to reduce diet-related GHG emissions can also bring co-benefits for other SDGs because climate-change brings hazards and uncertainties to global food systems. Increased average temperature, change of water availability and salinity due to elevated carbon dioxide levels in the atmosphere, would have negative impacts on the crop yields (Challinor et al., 2014) and even nutrient content of food crops. For example, Myers et al. (2014) reported reduced levels of zinc, iron, and protein in cereal and legume products under elevated carbon dioxide conditions. Evidence on reduced yields of fruits, vegetables, and legumes due to the increased water scarcity and salinity driven by climate change has also been reported (Scheelbeek et al., 2018; Alae-Carew et al., 2020). Nutrition-sensitive food policy (SDG 2) should therefore take the climate change impacts into account to minimize its negative nutritional consequences.

Dietary Change and SDG14—Life Below Water

SDG 14 focuses on the conservation and sustainable use of oceans, sea, and marine resources. The overapplication of nitrogen and phosphorus fertilizer in agriculture production and the associated runoffs drive the nutrient pollution of aquatic systems, impeding the mission of SDG 14 due to the eutrophication in coastal zones (i.e., target 14.1).

Earlier studies have identified that the replacement of nitrogen-intensive beef to poultry and a reduced consumption of animal- products could lower the nitrogen requirements thus mitigating the associated pollution in ecosystems (Bouwman et al., 2013; Bodirsky et al., 2014). Eutrophication emission impacts on average are high for animal-sourced products and farmed crustaceans (e.g., 300 g PO4eq/kg for beef, 50 g PO4eq/kg for poultry meat) and low for plant-based foods such as fruits, maize, and cassava with emission <5 g PO4eq/kg (Poore and Nemecek, 2018). The eutrophication potential embedded in per capita food intakes would reduce by 10–20% in high-income countries if people follow the national dietary guidelines that generally recommend a large replacement of meat, dairy, sugars, and oils with other crop foods (Behrens et al., 2017). A shift from current diets to the EAT-Lancet reference diet is projected to decrease the nitrogen and phosphorus application needs by around 10% globally (Willett et al., 2019).

Across regions, North America will have the largest environmental savings with a 38% fertilizer application reduction if they transition from their current diet to EAT-Lancet reference diet, followed by Europe and Central Asia with one quarter reduction (**Table 1**). As with other environmental impact domains, the N and P footprint in Sub-Saharan Africa and South Asia would increase by 30% or more because it entails increased intake amounts of most foods. The dietary shifts in the rest of world regions would reduce around 7–17% fertilizer-associated impact, except the increase in P demand for East Asia and Pacific and India.

Dietary change to mitigate the nutrient-pollution induced eutrophication and acidification and protect the life under aquatic ecosystems (i.e., SDG 14), would complement other on-farm efforts to improve the nitrogen and phosphorus use efficiency of different foods (Metson et al., 2021) by increasing N conversion for livestock production (Lassaletta et al., 2016; Groenestein et al., 2019) and reducing nutrient overuse during the cereal cropping practices especially in hotspot regions like China (Mueller et al., 2012), or to establish vegetative buffers to prevent the run-off from polluting water bodies (Ramesh et al., 2021). In addition, cutting down the food related carbon footprints (SDG 13) through dietary change also interconnects with the targets of SDG 14 as the elevated atmospheric GHG levels drive the ocean acidification (target 14.3) that in turn negatively affects the marine life (Doney et al., 2009; Kroeker et al., 2013; Lade et al., 2019).

Food production and consumption affect the life below water in multiple ways. Fisheries and aquaculture support the provision of fish and shellfish products which are important sources of protein and high bioavailable nutrients like polyunsaturated fatty

acids (Wallin et al., 2012; Zheng et al., 2012). The EAT-Lancet Commission recommends 28 grams of daily fish intake, yet the intake in current average diets is below this level across most regions except East Asia and Pacific (Willett et al., 2019). Thus, to close the existing nutrition gaps particularly in regions with high food insecurity, the consumption of fish and other edible aquatic animal products needs to increase across the globe through promotion of sustainable fisheries (Bogard et al., 2018; Hicks et al., 2019).

Currently, the fish sector in food systems is associated with ecosystem damage from overfishing and unsustainable aquaculture practices that result in damage to life under water (Diana, 2009; FAO et al., 2020). The indicator monitoring the SDG target 14.4 shows that fish stocks within biologically sustainable level have deteriorated from 90% of stocks in 1974 to 66% in 2017 and more than 30% have been overfished (FAO, 2020). Rapid expansion of aquaculture also contributes to the resource use and emission associated to fish meal production (Pahlow et al., 2015; Fry et al., 2016). Effective regulation on global fisheries is need of the hour that keeps the fish stocks within biologically sustainable levels and enables the sustainable expansion of aquaculture production to meet the SDG 14 targets.

Another issue to consider while increasing the intake of fish or seafood is the type of species or production systems supplying them because the environmental impacts of fish vary widely. Across fish and seafood species, mollusks from aquaculture can have beneficial impacts on ecosystem services (Naylor et al., 2021) with smallest emissions and energy use, while catfish aquaculture on average was found to be associated with larger environmental damages (Hilborn et al., 2018). Regarding production systems, the recirculating aquaculture and trawling fisheries have higher carbon footprints than other production methods due to fuel use, and fisheries involving bottom trawls have more ecosystem disruption on life under water (Clark and Tilman, 2017). Fish products from integrated agricultural-aquaculture system (e.g., rice-catfish) were found to be associated with relatively low environmental footprints (Clark and Tilman, 2017). Enhancing the supply chain technology including processing and packaging can help improve the environmental, nutritional, economic impacts of extensively integrating fish and seafood resources into diets (Bogard et al., 2018).

Dietary Change and SDG15—Life on Land

Notwithstanding the growing efforts, only one-third of countries are on track to achieve their national biodiversity targets (https://unstats.un.org/sdgs/report/2020/goal-15/). Agriculture is the largest driver of deforestation and land use change and occupies 40% of the global land surface (Foley et al., 2011). The expansion of agricultural land since twentieth century mainly occurred in biodiversity-rich tropical regions while the land area for food production in temperate regions shrunk (Willett et al., 2019; Estrada et al., 2020). As a result, the food-related land use is associated with the destruction or degradation of the natural habitats of many species driving them to the brink of extinction and impeding the progress toward the SDG 15 targets 15.1, 15.2, and 15.5.

Leclère et al. (2020) showed that adjusting dietary choices toward a lower portion of animal-based foods could reduce the pressure on the land for food production while satisfying the dietary energy and nutritional requirements for the growing human population. Reflecting the biodiversity hotspots, a shift toward more plant-rich diets could lower the extinction risks for various mammal and bird species of the tropical South America and the southeast Asia, India, and China (Tilman et al., 2017).

Several studies have shown that per serving of cereals, vegetables, and fruits require less cropland rather than livestock products and thus transitioning from animal-based to plant-based diet can reduce the demand for natural land clearing (Aleksandrowicz et al., 2016; Poore and Nemecek, 2018; Clark et al., 2019; Chaudhary et al., 2022). Others have shown that a shift toward the recommended healthy pattern (SDG 2 and 3) in affluent countries would co-benefit SDG 15 due to a lower land demand than current average footprints (Behrens et al., 2017; Ridoutt et al., 2020).

However, the cropland use reduction was found to be negligible if global food consumption transitioned toward the healthy diet that EAT-Lancet Commission recommended, with only 0-2% lesser land demand than current levels (Willett et al., 2019). According to their model, the reduction in land demand for animal products and feed crops was compensated by the increased demand for filling intake gaps of healthy foods like nuts and legumes, which are relatively low yielding in many national food systems (Willett et al., 2019). South Asia, Sub-Saharan Africa, India, and East Asia and Pacific are likely to have 20–50% increase in the cropland needs for adopting the EAT-Lancet proposed reference diet, while the adoption of such diet would reduce one quarter of land footprints embedded in food consumption for North America, Europe, and Central Asia (**Table 1**). At the national level, Chaudhary and Krishna (2021) showed that a shift toward sustainable diet in India would entail 33% higher per capita land footprint although this increased land demand can be met if the yield gaps of major crops are filled.

Several studies have explored the consequences of past, current and future human cropland use and individual food items on biodiversity (Machovina et al., 2015; Chaudhary and Kastner, 2016; Chaudhary and Brooks, 2018; Chaudhary et al., 2018c; Green et al., 2019; Willett et al., 2019; Leclère et al., 2020; Williams et al., 2020; Benton et al., 2021; Mair et al., 2021). Animal meat products in human diets are associated with disproportionately large biodiversity footprints and their demand is projected to further increase (Machovina et al., 2015), thus threatening biodiversity across the world (Leclère et al., 2020; Benton et al., 2021). Across crop foods, staples, sugarcane, palm oil, and cocoa exported from biodiverse and less affluent countries including Indonesia, Madagascar, Tanzania, and Philippines are the hotspots of natural habitat loss and degradation with consequent negative biodiversity impacts (Chaudhary and Kastner, 2016; Chaudhary et al., 2018c).

The specific location of cropland use influences the magnitude of the biodiversity impact because species are distributed non-uniformly in the world with higher species density in tropical regions. Transition toward a healthy diet might increase the clearance of natural habitats for agriculture purposes if regional

food systems do not consider biodiversity conservation as a goal. It thus calls for complementary strategies such as the optimized location of regional crop production to minimize the conflicts between food provision and biodiversity integrity of ecosystems (Erb et al., 2016).

Apart from the land-use induced habitat loss and threat, nutrient runoff and loading due to fertilizer application is also associated with damage to the ecosystem function and the terrestrial biodiversity jeopardization. Limiting the agricultural nitrogen and phosphorus footprint embedded in dietary choices (SDG 14) could also contribute positively toward the SDG 15.

DISCUSSION

According to current dietary demand trajectories and socio-economic development (e.g., population, income), global food-related environmental footprints are projected to transgress all five planetary boundaries by 2050 in terms of GHG emission, cropland, freshwater, and nitrogen and phosphorus application (Springmann et al., 2018a; Willett et al., 2019). Supply-side efforts such as closing yield gaps, agriculture expansion and intensification are either associated with an increase in resource inputs (e.g., fertilizer, water, land) or not enough to meet the global food demand by 2050 if continuing currents diets (Bajželj et al., 2014; Springmann et al., 2018a). Moreover, currently less affluent regions will expect a necessary growth in the consumption of diverse food products including animal protein for tackling food insecurity and malnutrition. A shift toward healthy and sustainable eating pattern worldwide as a key demand-side measure is therefore imperative for feeding the global population within a safe living space and progress toward SDGs.

The interactions between SDGs are complex and their connections are dynamic for different development levels (Pradhan et al., 2017; Wu et al., 2022). The co-benefits of dietary change for mitigating climate change and improving public health (e.g., obesity, cardiovascular diseases, nutrition) are often highlighted in different global and national modeling studies (Payne et al., 2016; Song et al., 2017). However, the implications for multiple SDGs can be mixed and divergent. For example, sustainable fish consumption needs to address the potential trade-offs between biodiversity in aquatic ecosystem (SDG 15), dietary nutrition (SDG 2, 3), and poverty (SDG 1), especially for the small-scale fishery communities and the coastal localities (Blanchard et al., 2017; Hicks et al., 2019). The decision-making in crop options (e.g., rice vs. sorghum in India) also needs to balance the dietary nutrition provision (SDG 2, 3) and the resilience of climate risks in agricultural production (SDG 13) (DeFries et al., 2016). The affordability (SDG 1) of a low-environmental-footprint (SDG 5, 6) and healthy (SDG 2, 3) diet is worth examination especially when considering the economic challenges for poorer communities (Reynolds et al., 2019; Penne and Goedemé, 2020; Gupta et al., 2021). Overall, our review advocates the need for comprehensive assessments that can reveal the potential trade-offs and support an optimal decision-making. **Supplementary Table S1** summarizes the studies looking at the connection between dietary change and sustainable development goals (SDG) indicators.

Here in sections below we briefly discuss how to achieve this dietary transition. No single stakeholders or actors can catalyze the dietary change; the food producers, industries (e.g., packaging, marketing), service providers (e.g., menu in restaurants and school canteens), policy makers (e.g., fiscal interventions), and food-related culture norms (e.g., traditions, habits, cooking skills) and so forth would have to together drive this transition.

Consumer Behavior Change

Consumers make personal choices on what they eat according to individual preference, meanwhile their choices are also shaped by their cultural or religious background as well as the food environment that are composed of various food-related activities such as available foods in local markets, food price, the perceived product properties, marketing, and regulation (Herforth and Ahmed, 2015; Bianchi et al., 2018; Turner et al., 2018).

To broadly achieve a shift from current diets to sustainable healthy dietary choices, the latest scientific knowledge from consumer behavior studies could help design the measures. For example, the social norms including the peer's engagement or positive evaluation on vegetarianism and the self-efficacy meaning a belief in the power of mitigating the adverse environmental effect *via* dietary shifts are the top two factors that drive the behavioral change in food consumption context (Eker et al., 2019; van Valkengoed and Steg, 2019). For local communities, campaigns that target modifying the social norms on dietary habits may contribute to dietary change behaviors (Rust et al., 2020).

The growing body of scientific evidence reveals the magnitude of benefits from adoption of sustainable diets, and this can strengthen the perceived self-efficacy if the findings can be clearly communicated to different stakeholders and broad audience. For example, consumers tend to underestimate the environmental impact of food products, thus providing them correct impact information through intuitive indicators (e.g., in units like light-bulb minutes or number of cars on road) as product labels could facilitate more sustainable purchase choices (Camilleri et al., 2019; Siegrist and Hartmann, 2019). Particularly in high-income countries, people given health co-benefit information are likely to show more willingness to adopt the environmentally-friendly products or diets (Amelung et al., 2019). For global and national food-based dietary guidelines, consideration of the potential impacts on human health and the environment together is therefore of importance to drive dietary behavior changes (Lazzarini et al., 2018; Howe et al., 2019).

Apart from the conscious determinants of dietary behaviors like values and knowledge, the non-conscious and non-reasoning behavioral processes may also have a discernible impact on individual demand (Marteau, 2017). Reconstructing the physical micro-environments such as reducing meat serving size, providing meat alternative products with educational information, and changing the sensory characteristics of the products, were found to be effective in reducing meat consumption which in turn has sustainability benefits (Bianchi

et al., 2018; Rust et al., 2020). Similarly, placing more sustainable and healthy product options on retail shelf and menu and making them visually prominent can increase their consumption (Garnett et al., 2019).

Monetary and Fiscal Interventions

Apart from individual behavior changes, fiscal interventions can also drive the transition from current to sustainable dietary behaviors. A sugary drink tax in Mexico has decreased their consumption by 7.6% with the greatest reduction effects among low-income households that reduced purchases by 11.7% (Colchero et al., 2017). The tax on sugar-sweetened beverages in UK was found to drive product-reformulation by food industries, reducing sugar intake from soft drinks and inducing positive population health outcomes like obesity reduction (Briggs et al., 2017; Bandy et al., 2020).

Fiscal measures like levying carbon tax on food products could be a viable option for addressing the hidden cost associated with the foods and motivate a shift toward sustainable and healthy dietary patterns (Edjabou and Smed, 2013; Pieper et al., 2020). Though varying across regions, a global carbon emission tax would increase the market price of animal source products the most due to their substantially high GHG emissions and consequently the consumption of beef, milk, and lamb would have the most reduction (Springmann et al., 2017). On the other hand, health related taxes on food products which are high in added sugar, unhealthy fats, or carcinogens could also help improve the dietary quality and decrease food related chronic disease risks (Springmann et al., 2018b; Waterlander et al., 2019; Blakely et al., 2020).

However, such taxes should not hinder the progress toward ending hunger and malnutrition (SDG 2), especially for low-income households who will be unable to purchase sufficient and nutritious foods if the price is raised. To avoid this scenario, the revenues of environmental tax could be recycled to the consumers *via* lowering the price of healthier and sustainable food like fruits, vegetables, and plant-based protein products. This revenue recycling can involve direct subsidization (Olsho et al., 2016; Springmann et al., 2017) or the capital investment on sustainable alternatives (Mason-D'Croz et al., 2019a,b). The combination of taxes and subsidies for respective food categories could help address the underlying dilemma that people living with poor diets cannot afford the recommended nutritious foods like fruits, vegetables, nuts, and legumes (Hirvonen et al., 2019).

Regarding the investments in food systems to achieve SDGs, developing quantitative indicators capable of discerning the sustainability performance of alternative products (Chaudhary et al., 2018b; Chaudhary and Tremorin, 2020; Mair et al., 2021) and the economic valuation of sustainability benefits from dietary change (Springmann et al., 2016) could help to guide the industrial investors and other stakeholders. Governments could remove systemic barriers (e.g., policy instruments, subsidies, etc.) to such investments for creating an environment that cooperates with capital interests and stimulates the business models in favor of human wellbeing and ecosystem integrity.

To adopt the healthy diets, food systems should improve their supply of affordable, palatable, diverse, and acceptable food commodity options (e.g., plant-based protein sources, fruits, vegetables) for people worldwide (Ferreira et al., 2021). Policy in this case could help advance the development priorities such as high yielding crop varieties of insufficient foods [e.g., legumes and nuts in undernourished regions; Ofori et al., 2021], resource-efficient agriculture practices (Davis et al., 2017; Rosa et al., 2018; Rothrock et al., 2019; van Wijk et al., 2020; Jin et al., 2021; Obirikorang et al., 2021), sustainable fisheries management, alternative food and feed (Gold et al., 2018; Caporgno et al., 2020) through fiscal and other interventions.

Current Data Gaps

Previous global assessments often rely on the food balance sheet data from United Nations Food and Agriculture Organization (FAO, 2019) to derive the average dietary intake estimates at the country level. However, the intake amounts of only 98 primary commodities are available here while in reality people consume hundreds of processed food products which has implications for actual nutrient intake as well as environmental footprints (e.g., nutrient content and footprint of pizza or pasta is different from its primary product wheat). Although GENUS database (Smith et al., 2016) improved the resolution to 225 food items, the intake amounts of many processed items remain elusive for most countries. Also, in addition to national average data, the dietary intake data should be available for different age, gender, region, or income groups for a given country to better understand the nutritional inadequacies for devising interventions.

The dietary guidelines should also improve the food item resolution taking into account cultural acceptability of the region (Chaudhary and Krishna, 2019). For example, the EAT-Lancet reference diet includes 16 broad food groups with wide intake ranges and exchangeable options (e.g., a set of animal and plant protein sources), which needs further fine tuning for individual food items to be more useful for personal and policy decision-making. Emerging platforms like Food System Dashboard (Fanzo et al., 2020), Global Burden of Disease (GBD), and Global Dietary Database (Khatibzadeh et al., 2016) have aggregated extensive data-based evidence to provide accessible information on food system and its impacts.

The food composition databases providing nutrient content per unit mass of foods also need to include data for food items in the final form in which they are eaten (e.g., pizza instead of just wheat). Processing of foods through cooking can leads to nutrient loss and thus considering primary food items instead of final processed ones can lead to overestimation of nutrient adequacy of diets.

Huge efforts are still needed to come up with accurate environmental footprints of different food items produced in different parts of the world. Previous studies have done significant works to collect the scattering data points on environmental footprints of foods in different regions and production systems (Mekonnen and Hoekstra, 2011; Clark and Tilman, 2017; Clune et al., 2017; Poore and Nemecek, 2018; Springmann et al., 2018a,b) but gaps

remain. For example, emission changes mediated by the soil carbon stock were insufficiently addressed in climate change implications of dietary strategies (Ridoutt et al., 2017). The water footprints should better take into account the local water scarcity situations (Clark et al., 2019).

Other issue is quantifying the impact of diets on multiple domains of the environment rather than on a selected few. Most existing research focuses on climate change, land use, and water use impacts, while other impact categories are rarely addressed (Ridoutt et al., 2017). Environmental burdens such as biodiversity losses (Chaudhary et al., 2015, 2018c), chemical toxicity from pesticide use, air pollution linked with food production (Lelieveld et al., 2015; Blackstone et al., 2018; Domingo et al., 2021) have not been well quantified when evaluating the impact of global dietary changes. For environmental sustainability, the future dietary change studies can utilize recently proposed environmental footprint family that are directly linked with the SDG framework (Vanham et al., 2019).

Finally, a harmonized dataset on price of different food items in different parts of the world is need of the hour. The low affordability of healthy and sustainable diets could be the key barrier of realizing dietary changes around the globe while previous assessment such as EAT-Lancet commission often failed to examine the economic feasibility of recommended dietary transitions due to the lack of robust data. This would entail expanding existing programs such as International Comparison Program (ICP) of World Bank to include more food items and making it open-access or compiling retail food price data from local supermarkets across the globe.

As shown in **Supplementary Table S1**, indicators used in the past dietary change studies did not always align with global SDG indicator framework (United Nations, 2021). In future, the indicator identification could consider a SMART manner (specific, measurable, attainable, relevant, time-based) and learn from the representative case studies in different regions (Germann and Langergraber, 2022). In the end, all indicative numbers are tools to help capture the benchmark, progress, as well as the complexity of sustainability, with the ultimate goal being locally feasible actions in real world. The scope of this review was to provide an overview of the studies that have shown how changing our current diets can help us make progress toward six different SDGs, but future studies should carry out an in-depth quantitative analysis on the potential of dietary change to contribute toward progress on individual SDG indicators (Germann and Langergraber, 2022).

We acknowledge that SDG 1 (No poverty), SDG 5 (Gender equality), SDG 8 (Decent work and economic growth), SDG 10 (Reduced inequalities), SDG 12 (Responsible consumption and production), and other SDGs are also interconnected with the performance of food systems (Chaudhary et al., 2018a,b,c; Alarcon et al., 2021) but presenting quantitative evidence on their linkages is beyond the scope of this review. Future research efforts should focus on filling this gap and present the implications of dietary change for other SDG targets.

CONCLUSIONS

Agricultural production to feed increasing world population with rising income levels and globalization is one of the leading causes of climate change, ongoing biodiversity extinctions, land degradation, water pollution and ecosystem service loss (Kastner et al., 2021). Yet, the diets of almost all nations lack in one or more micronutrients (vitamins, minerals) essential for human wellbeing (Chaudhary and Krishna, 2019; Chen et al., 2021). Widespread economic inequalities and the supply instability risks under emerging disturbances like the pandemic and climate change may increase the risk for inadequate and unsustainable diets in near future and thus calls for urgent research and policy efforts (Kimani-Murage et al., 2021).

Applying a consistent Sustainable Development Goals (SDG) framework, here we carried out a quantitative review of over 200 published articles aiming to inform national policy makers and food business companies on which food items and nutrients should be promoted or discouraged in different countries of the world to achieve nutritional security and meet environmental targets.

We highlighted the existing evidence that dietary changes can lead to win-win outcomes for human society and the planet revealing the heterogeneity of dietary patterns and the associated sustainability impact across the world. The dietary change strategies should consider the diverse needs (e.g., undernutrition vs. diet-related non-communicable diseases) and regional-adaptive solutions (e.g., local food availability, regional production condition, food preferences, trade partnerships).

Unlike past reviews focusing on a particular world region, sustainability aspects, or limited number of metrics, the main strength of our review is the consideration of six SDGs simultaneously as well as the use of several indicators of environmental footprint (GHG emissions, freshwater use, land use, biodiversity loss, nitrogen, and phosphorus application) and nutritional quality for all countries of the world. This enables in identification of geographic hotspots and highlights potential trade-offs in achievement of different SDGs and underscores the need for breaking silos and adopting an interdisciplinary approach to solve these problems. No single stakeholders or actors can catalyze the dietary change toward sustainable food consumption. Contributions for the food producers (farmers), industries (e.g., packaging, marketing), service providers (e.g., restaurants, retail, school canteens), policy makers (e.g., those designing fiscal interventions), and food-related cultural norms (e.g., traditions, habits, cooking skills) and others would together drive this transition.

AUTHOR CONTRIBUTIONS

CC conceived the ideas, designed the study, compiled data, carried out analysis, and wrote the first draft. AC conceived the ideas, designed the study, and wrote the manuscript. AM provided comments on manuscript. All authors have

critically reviewed the manuscript for the intellectual content and approved the final version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.771041/full#supplementary-material

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Promoting dietary changes for achieving health and sustainability targets

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Globally, about 21–37% of total greenhouse gas (GHG) emissions are attributable to food systems. Dietary-related non-communicable diseases have increased significantly from 1990–2019 at a global scale. To achieve carbon emissions targets, increase resilience, and improve health there is a need to increase the sustainability of agricultural practises and change dietary habits. By considering these challenges together and focusing on a closer connection between consumers and sustainable production, we can benefit from a positive interaction between them. Using the 2019 EAT Lancet Commission dietary guidelines, this study analysed interview data and food diaries collected from members of Community Supported Agriculture (CSA) schemes and the wider UK population. By comparing the environmental sustainability and nutritional quality of their respective diets, we found that CSA members consumed diets closer to the EAT Lancet recommendations than controls. We identified significant differences in daily intakes of meat; dairy; vegetables; legumes; and sugar, and the diets of CSA members emitted on average 28% less CO2 compared to controls. We propose that agricultural and wider social and economic policies that increase the accessibility of CSAs for a more diverse demographic could support achieving health, biodiversity, and zero-emission policy targets.

KEYWORDS

consumption, healthy, environmentally sustainable, zero emission targets, community supported agriculture, EAT-lancet diet

1. Introduction

Food systems, and in particular, food production, are key to both mitigation of climate change and resilience to the impacts of climate change. Shifting consumption towards healthy and sustainable diets is a significant opportunity for reducing greenhouse gas (GHG) emissions from food systems and improving health outcomes (Mbow et al., 2019).

Globally, about 21–37% of total greenhouse gas (GHG) emissions are attributed to food systems, specifically agriculture, land use, storage, transport, packaging, processing, retail, and consumption (Mbow et al., 2019). Of these GHG emissions, 9–14% are attributed directly to agriculture itself (Mbow et al., 2019). With the UN Climate Change Conference of the Parties (COP) 28 convening in the UAE in 2023 to discuss the goals of the Paris Agreement and the UN

Framework Convention on Climate Change, discussions about the resilience and sustainability of the global food system are increasingly salient. Given commitments to achieve zero emission targets by 2050, reorienting the global food system to deliver healthy food using low carbon methods is key to achieving this commitment. In 2021 and 2022, there were many subnational governments and civil society organisations supporting initiatives like the Glasgow Declaration calling for action to reduce GHG emissions from food systems, build sustainable food systems and deliver safe, healthy, accessible, affordable, and sustainable diets for all (IPES-Food and Nourish Scotland, 2020; CGIAR, FAO and The Rockefeller Foundation, 2022), demonstrating both a clear commitment to tackle the climate emergency through integrated food policies, and pressure on national governments to act. At COP 27, for the first time, agriculture featured as one of the thematic days and the number of COP pavilions with all-day programming on food and agriculture issues jumped from zero to five. "There will be many opportunities to make further progress on food, agriculture, and climate in the year ahead —thanks to the newfound prominence on the global climate agenda" (United Nations Foundation, 2022).

Whilst agriculture has a role to play in mitigating climate change, it is also subject to the impacts of climate change such as drought, storms and flooding. Understood in resilience terms, these are climate change-induced shocks to the food system. The Intergovernmental Panel on Climate Change defines resilience as the capacity of interconnected social, economic and ecological systems to cope with such 'shocks': hazardous events, trends or disturbances, responding or reorganising in ways that maintain their essential function, identity and structure (IPCC, 2019). A resilient food system is robust, able to recover quickly after disruption or shocks, and actively reorienting towards more sustainable environmental and health outcomes (Global Food Security, 2019). Nearly every nation in the world (191 countries plus the European Union) has joined the Paris Climate Agreement to the United Nations Framework Convention on Climate Change (UNFCCC), to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change" (United Nations (UN), 2015, p. 3). The mitigation potential of dietary changes, to more sustainably produced food with less meat consumption, is estimated as 0.7–8.0 GtCO2-eq yr–1 by 2050 (Mbow et al., 2019). Sustainable food production systems would also increase ecosystems' ability to resist and recover from extreme weather, thereby increasing resilience of food production (Food Farming and Countryside Commission, 2021).

From a health perspective, there is also potential to enhance public health resilience to diseases by shifting to healthier diets. A population that consumes healthier foods is more likely to be robust against threats posed by both non-communicable diseases (e.g., type II diabetes, cardiovascular disease and certain cancers), and communicable diseases (e.g., influenza, COVID-19) (Afshin et al., 2019). People who achieve better nutrition levels, which are associated with favourable physiological parameters such as lower body mass index and lower prevalence of hypertension, are also likely to recover more quickly from acute and chronic illnesses.

Thus, dietary change is a key way in which both carbon emissions and public health can simultaneously be addressed. The 'EAT–Lancet Commission on healthy diets from sustainable food systems' (Willett et al., 2019) recommended a 'reference diet' (the 'EAT' diet), based on a literature review of existing dietary patterns and the health and environmental outcomes associated with different foods. As far as existing data allowed, Willet et al. aimed to provide a generally applicable evidence-based target diet, which could be refined to account for local variation in existing diets, as well as cultural and environmental factors. The EAT diet largely comprises non-starchy vegetables, fruit, grains, legumes (pulses), nuts, seafood, poultry, dairy products, with a small amount of starchy vegetables, red meat, processed meat and added sugar. Since the publication of the report there have been a small number of studies aiming to build upon and discuss its findings and recommendations.

Springmann et al. (2020) modelled the effects of the hypothetical adoption of existing 85 national dietary guidelines on health and environment and compared these outcomes with two global dietary recommendations: the World Health Organisation's (WHO) recommendations and those of the EAT–Lancet Commission. This study found that the recommendations developed by the EAT-Lancet Commission are associated with greater health benefits than the national level and WHO dietary guidelines and would reduce environmental resource use in line with internationally agreed targets. Another study found similar results, proposing that a difference in approach was the underlying reason for the projected high efficacy of the EAT diet (Blackstone and Conrad, 2020). They argued that national guidelines are policy documents which, though informed by existing evidence on health, are developed within a health policy context that takes a harm reduction approach (small changes to diet can have a large effect on health, whereas difficult to achieve recommendations risk overwhelming citizens). Many national level targets are less certain about whether sustainability is a societal concern that should be integrated into government guidelines on diet, or a matter of individual choice; they are 'gently' normative about health, but less so about sustainability (Santaoja and Jauho, 2020). One contrary example to this is Wales. In their Carbon Budget for 2021–2025, Welsh Government states, "Welsh Government has agreed to develop a long-term strategy to promote a dietary shift towards the UK Government's 'EatWell Guide' by encouraging Welsh consumers to eat healthier, more sustainably sourced food, to eat and waste less." (Welsh Government, 2021, p. 156).

There are examples of studies which examine how the EAT diet could be adapted to account for cultural and social context, with Lassen et al. (2020) offering two regimens based on data on Danish diets and national dietary guidelines as well as consideration of the limitations of change within this context. Reynolds et al. (2019) contributed an analysis of UK diets and greenhouse gas emissions which offers similar insights for different income groups within the UK population, indicating that a more sustainable diet would look different for different segments of the population, accounting for the affordability of different foods and the differing cooking and eating habits of people within British society. They argue for a tailored approach which is informed by social and income constraints within the population to achieve maximum success in reducing the environmental impacts of dietary habits.

1.1. Achieving sustainable healthy diets in the UK

Building upon this body of work, our study aimed to consider how a healthier and more environmentally sustainable diet could

be achieved given commitments under the Paris Agreement. The data collected herein relate to UK households, but the results and lessons learned are applicable across the world, where globalised food supply chains have increased the distance between producers and consumers and alienated consumers from the source of their food. In line with Article 4 of the Paris Agreement, the UK Government has committed to a 68% reduction in GHG emissions (compared to 1990 levels) by 2030 (UK Government, 2020). As part of its commitment to the UNFCCC the UK has said it will deliver a national shift to healthy diets supported by sustainable food production which contributes towards a reduction in GHG emissions. Around 61% of UK citizens are overweight or obese, resulting in approximately 70,000 premature deaths annually due to diet-related ill health (The Parliamentary Office of Science and Technology, 2020). The UK is in a unique moment of change as it navigates the disruption of the COVID-19 pandemic and the war in Ukraine on food supply chains and the increase in household food insecurity to 20% (Armstrong et al., 2023), as well as its exit from the European Union, and the resulting new trade agreements and domestic agricultural policies. These changes create a window of opportunity for implementing changes across the food system that can result in healthy, environmentally sustainable and accessible diets for all. To investigate how an EAT diet could be achieved, we focus on a sub-population of people motivated by health and environmental concerns who have joined a Community Supported Agriculture (CSA) scheme and compare their food behaviours to a randomly selected control group.

1.2. Community supported agriculture

A CSA is a partnership between farmers and consumers in which the responsibilities, risks and rewards of farming are shared (European CSA Research Group, 2016; Community Supported Agriculture Network UK, 2020). Whilst there are a wide variety of governance arrangements amongst CSAs, the consumer typically offers something more to the CSA than just a straightforward exchange of money for produce. For example, they may contribute labour, take some financial risk or invest in the CSA, play a part in decision-making, and/or accept a variable share of produce. CSAs are established as a sizable part of the agricultural sector in the USA and France, with 3,000 and 12,500 active CSAs respectively, but are still only a very small part of the food system in the UK, which has 179 CSAs, many of which are not yet wholly established or are inactive (Saltmarsh et al., 2011; Community Supported Agriculture Network UK, 2020).

There are a few studies that have examined how CSA membership may affect diet (Wilkins et al., 2015; Allen IV et al., 2017; Hanson et al., 2017), which suggest that there may be movement towards more healthy and sustainable diets in this population. However, there is little evidence of this in the UK context and what it would mean for meeting net zero GHG targets. In this paper, we examine whether CSA members consume a diet that more closely resembles the EAT diet than non-CSA members in the UK. We aimed to answer the following research questions:

1. Are CSA participants' diets more environmentally sustainable than those of control group participants?
2. Are CSA participants' diets more nutritious compared to those of control group participants?

2. Methodology

We used semi-structured interview data and food diaries collected from members of CSA schemes and the general population to compare environmental sustainability and nutritional quality of diets between these two groups. We hypothesised that CSA members engage in a diet that is healthier and more environmentally sustainable than the general UK population.

2.1. Recruitment

A total of 113 participants were recruited (CSAs $n=46$, control group $n=67$). Participants in the CSA group were recruited through collaboration with four CSA organisations (two in South Wales and two in Southeast England). In this case, we purposely recruited CSA members who had joined within the last year, since one of the aims of the wider study (not reported upon in this paper) was to explore if and how joining a CSA might change food behaviours over time. Participants were given an incentive to join the study, receiving either free organic vegetables from the host CSA or a similar financial equivalent. The control group was recruited by approaching shoppers at random outside supermarkets local to the CSA schemes. Control group participants were provided with a similar incentive for taking part in the study, namely shopping vouchers which could be redeemed for goods. The main research challenge with both groups was scheduling the interview to fit into participants' busy everyday lives; as a result, some participants dropped out, and thus the difference in the number of participants in the two groups. An application of research ethics was approved by Cardiff University School of Geography and Planning ethics committee. Participants gave written consent after reading a participant information sheet and having had the opportunity to ask questions. The participant information sheet detailed the purpose of the study, why they were being invited to participate, confidentiality and anonymity, how their data was to be used and protected, what they needed to do to participate, and how study results would be used.

2.2. Semi-structured interviews

One-to-one interviews were conducted with CSA members and control group participants either face-to-face, by phone or *via* Zoom (depending on preference and timing of interviews). We asked participants about their household food culture, i.e., their food purchasing, preparation and consumption routines, and their views and attitudes towards their dietary approach. The interview also collected some basic socio-economic data: the age, gender and occupations of the members of each household, as well as overall household income. Participants were encouraged to discuss their household food practises in depth, giving the interviewer some insight into why they might choose particular options. This depth was gained by asking follow-up questions to probe emerging themes and concepts brought up by the interviewee. All interviews were audio-recorded, transcribed and anonymized.

2.3. Dietary recall with intake24

After the interviews, research participants were requested to complete food diaries for three consecutive days using Intake24

software (see below). Food diaries were anonymised and were conducted online. We analysed a total of 162 food diary entries, with 97 entries from CSA members and 64 entries from the control group participants. Participants were advised to choose two weekdays and a weekend day that best represented their typical food and drink intake as far as possible. Data collected from the food diaries was used to verify the accuracy of interview responses regarding general patterns of weekly food consumption.

Intake24 is an online 24 h dietary recall system that enables users to self-report their dietary intake. The tool is based on the automated multiple pass method and has over 2,400 food photographs featuring more than 100 foods for portion size estimation based on reporting in the UK National Diet and Nutrition Surveys (Smithers et al., 2000). Photographs have been previously validated against four-day weighed intake records and in a feeding study (Foster et al., 2008, 2010). More than 2,300 foods are included in the database, which is regularly expanded to include new foods. Intake24 also incorporates a 'missing foods' function which permits users to identify any foods or drinks that are not currently available. An additional tool enables participants to 'make your own sandwich/salad' and add their own recipes. GHGs associated with each food group were drawn from an extensive database of GHG data linked to all foods identified in the National Diet and Nutrition Survey (Bates et al., 2019) and were reported as grammes of carbon dioxide equivalent (gCO_2e). A video tutorial outlines the main features of the system and contextual help buttons provide additional guidance on specific features.

2.4. Data analysis

Calorie intake for CSA and control group participants was estimated for each of the food groupings highlighted in the EAT Lancet dietary guidelines, namely wholegrains, tubers/starchy vegetables, vegetables, fruits, dairy foods, protein sources (beef/lamb/pork, chicken/other poultry, eggs, fish, legumes, nuts), added fats and added sugars. Due to some discrepancies between food groupings used in Intake24 and EAT Lancet guidance, certain foods were re-classified for our analysis according to a hierarchical process based on the dominant food ingredient (for example, sweet pastries were classified as sugar, whereas savoury pastries were classified as wholegrain, unless they were meat pastries, which were classified as meat (see Appendix 1). Data for CSA and control group participants were analysed using the SPSS 26 statistical software package to compare means for participants' daily consumption between the two groups. Analysis of variance (ANOVA) was used to compare the CSA and control group for all EAT Lancet food categories, as well as for income, overall daily caloric intake, fat, saturated fat, sugar, protein, carbohydrates and gCO_2e. Ordinal regression analysis was also used to compare frequency of organic produce purchases between the CSA and Control groups.

2.5. Strengths and limitations of the methods

Our approach of using food diaries and semi-structured interviews made it possible to triangulate consumption data and derive insight into the drivers behind trends in food diary data, for example, why CSA members consumed more vegetables. We included members from four CSAs in England and Wales, which resulted in data from different geographical areas, enabling potential generalisation of our findings. The use of Intake 24, an objective dietary assessment tool, which has favourable validation, gives validity to the accuracy of the dietary data and made it possible to consider a wide range of dietary components as well as environmental impact (gCO_2e). The finding that dietary data corresponded well with self-reported consumption patterns in the interview data also indicates the veracity of interview results.

The study has the following limitations. Firstly, to compare the Intake24 output with the EAT diet, we had to convert NDNS food categories, of which there were 118 categories, into the 13 EAT diet categories (see Appendix 1). Certain NDNS food categories could potentially be classified into multiple EAT diet categories (e.g., meat pasty), with resulting imprecision in the allocation of associated gCO_2e. See Appendix 1 for how NDNS food categories were grouped and the rationale. Secondly, greenhouse gas emissions were used as a single measure of environmental impact, when in reality there are many other environmental impacts associated with dietary choices (e.g., impacts of pesticides, herbicides and synthetic fertilizers, erosion and water use).

3. Results

3.1. Socio-economic characteristics

Our study showed a significant difference in age, income and socio-economic status between the CSA members and control group, which may mean some of the differences between our groups could be attributed to age, household income or socioeconomic class. The ANOVA analysis showed that there was a difference in age and average household adjusted income: age for the control group was slightly higher, and income was lower, when compared to the CSA group (value of p <0.10) (see Table 1). The most recent reliable data from the Annual Population Survey (Office of National Statistics, 2021) indicates that our control group is similar in its occupational status to the UK population. The results from an ordinal regression analysis of Socio-Economic Classification (Office of National Statistics, 2020) and CSA and Control group participants gave statistically significant results (value of $p = 0.000$), with a positive CSA coefficient value (2.76), which suggests that participants in the CSA group have above average socio-economic status: they are more likely to be employed in higher professional and managerial occupations than participants in the control group.

TABLE 1 Results from ANOVA for income [equivalised household disposable income, using the modified Organisation for Economic Co-operation and Development (OECD) scale] and age.

Dependent variable	Control group mean	CSA group mean	*F*-value	value of *p*
Age (years)	51	46	2.888	0.092
Income (£/year)	£27,115	£35,254	13.707	0.000

3.2. Dietary findings

We found significant differences between the CSA members and our control group in daily intake of food groups for beef, lamb and pork; dairy; vegetables; legumes; and sugar (calories day^{-1}) (see Table 2). The means for daily nutrient intake for fat, saturated fat, protein, carbohydrates, sugar, and the consumption-associated calculated gCO_2e were also significantly different (Table 3).

CSA diets emitted on average 28% less gCO_2e compared to the control group diet. There was no significant difference in mean daily caloric intake between groups. Thus, whilst total calories consumed were not different, dietary composition differed significantly across a broad range of components.

Of our control group, 3% were vegetarian and 1.5% were vegan (see Figure 1A). A greater proportion of CSA members reported having some form of dietary preference other than omnivorous with: 13% vegan, 6.5% vegetarian and 4% pescatarian. The CSA group had a larger percentage of participants that never ate meat: 26%, compared to 6% in the control group. We found that 94% of control group members and 60% of CSA members ate meat at least once or twice a week (Figure 1B). This is also reflected in the food diary data.

We found that 89% of our control group ate dairy at least once a week, with 77% eating it every day. CSA members reported eating and drinking dairy products less frequently and consuming smaller amounts than did the control group (Figure 1C). Eating fish regularly (once a week or more) was similar for CSA members (61%) and the control group (59%). However, not eating fish at all was more common amongst CSA members (22%) than the control group (8%; see Figure 1D).

The food diary data ANOVA analysis showed a statistically significant difference between CSA and control group for vegetable consumption, with CSA participants consuming an average of 47% more calories from vegetables. In an unprompted open question 37% of CSA participants mentioned eating a wider variety of quality vegetables, 27% reported eating more vegetables, 22% reported enjoying an improved quality and taste of their vegetables, and 10% of participants mentioned putting the vegetables they receive at the centre of their meal planning since they had joined a CSA. Finally, whilst meat consumption was lower for CSA members, legume consumption was greater for CSA members, as was confirmed by the interview data (Figure 1E).

The EAT-Lancet Commission also recommends cutting down on processed food. Both CSA members and the control group prepared most of their food from basic ingredients, although this tendency was more pronounced amongst CSA members: 93% of CSA members prepared their main meal from basic ingredients 4 times or more a week, whereas in control group households this figure reduced to 77%. This trend was reflected in how households described their use of prepared or processed foods in cooking. Approximately 20% of both groups reported never using pre-prepared or processed foods at home. Of the remaining households, 56.5% of CSA members and 48% of control group households reported preparing their main meal with pre-prepared ingredients once a week or less. Often households had a few things they regularly bought ready-made, like passata, chips, Quorn, or canned beans, whereas others usually cooked with basic ingredients every day, but supplemented their children's meals with some processed foods, e.g., "I cook a meal from scratch every day, but also supplement with processed food which the kids will eat, like pizza, garlic bread, pasta and sauce from a jar" (Interviewee OT6).

TABLE 2 Mean daily calories consumed by the control group and the CSA group according to EAT Lancet food category and comparison with dietary recommendations.

Food group	EAT lancet diet	CSA diet	Control group diet	value of *p*
Whole grains	811	609	505	0.201
Tubers and starchy vegetables	39	93	100	0.749
Vegetables*	78	93	43	0.001
Fruits	126	117	103	0.512
Dairy foods*	153	205	284	0.065
Beef, lamb and pork*	30	46	121	0.029
Chicken and other poultry	62	46	59	0.500
Eggs	19	25	45	0.154
Fish	40	40	32	0.625
Legumes*	284	42	19	0.077
Nuts	291	66	33	0.176
Added fats	450	11	4	0.273
All sugars*	120	268	389	0.107

*Indicates a statistically significant difference between the control and CSA groups, with value of p <0.10.

TABLE 3 Results from ANOVA run for aggregated daily food consumption, comparing the control group with the CSA group for key variables indicating health and sustainability of diet.

Daily intake	Control group mean	CSA group mean	*F*-value	value of *p*
Calories (kcal)	1737	1,655	0.348	0.556
Fat (g)*	101	64	4.959	0.027
Saturated fat (g)*	31	20	9.262	0.003
Protein (g)*	74	56	6.569	0.011
Carbohydrates (g)*	212	178	3.085	0.081
Sugar (g)*	106	70	11.980	0.001
GHG emissions (gCO_2e)*	3,823	2,995	5.313	0.022

*Indicates a statistically significant difference between the control and CSA groups, with value of p <0.10.

3.3. Environmental outcomes

In addition to the 28% difference identified in gCO_2e between the control group and CSA members, further sustainability impacts were illustrated by the interview data on organic food purchases. We asked participants how often they purchased organic produce, when the option was available (Table 4). Analysis yielded statistically significant results showing CSA members were likely to purchase organic foods more frequently compared to control group participants, with coefficient value −1.76 and value of $p = 0.000$. This would likely have a positive impact on environmental sustainability both with respect to gCO_2e and for biodiversity and water and air pollution (Clark and Tilman, 2017; Willett et al., 2019).

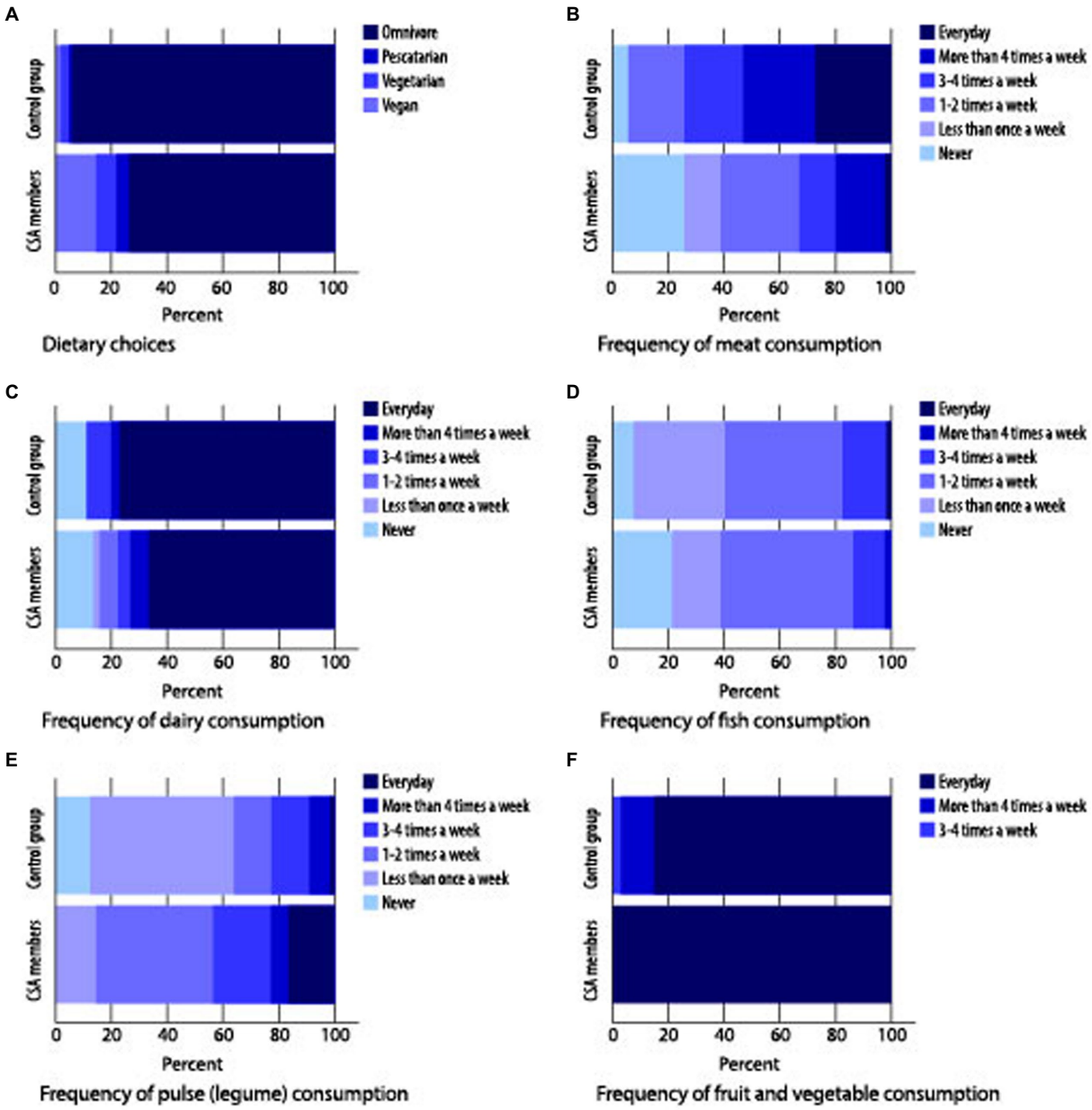

FIGURE 1
Stacked bar charts for interview questions answered by CSA members (n=47) and control group (n=67) participants showing the percentage of each group adhering to different dietary choices **(A)**, and the frequency of their consumption of meat **(B)**, dairy **(C)**, fish **(D)**, pulses (legumes; **E**, and fruit and vegetables **(F)**.

In response to an open-ended question of whether receiving a vegetable box had changed the way they cook or impacted their diet, 22% of CSA participants reported eating more healthily since joining the CSA. This was attributed both to eating a wider variety of quality vegetables, and to knowing that the vegetables were produced organically. When asked for their reflections on dietary changes 26% of participants mentioned that receiving the vegetables meant they ate in a way that they perceived to be more environmentally sustainable.

3.4. Drivers of dietary changes

Interview data indicated that CSA participants decided to join a CSA for the following reasons: 50% wanted to source food locally, 42% were interested in growing food as part of a community group, 54% had environmental concerns and 27% wanted to grow their own food. These motivations were embedded within the participants' specific circumstances and life experiences. Health conditions (cancer/tumours, heart disease/high blood pressure, allergies) sometimes provided a reference point, which participants referred to when they talked about the lifestyle changes they hoped to make or were already embarking upon. These personal circumstances could be entwined with wider changes that participants believed needed to happen within society more generally. Sometimes they saw the CSA as a way of contributing towards a more environmentally sustainable local economy. Often participants felt positive about the origins of their vegetables and that made them feel good about themselves: "A feel-good feeling of knowing their food is produced

TABLE 4 Cross tabulation of frequency of purchasing organic food when grocery shopping (as often as possible, half of the time, less than half of the time, never) comparing CSA members and control group participants.

	Control group	CSA group	Total
As often as possible	8	19	27
Half of the time	9	13	22
Less than half of the time	12	7	19
Rarely or never	37	8	45
Total	66	47	113

organically, is good quality, which has not been affected by the application of all sorts of nasty chemicals, fertilizers and pesticides" (SF10).

There seemed to be a group of linked positive effects attributable to membership of a CSA and/or receiving produce from a CSA. Visiting the CSA site improved mood and mental health for some participants, there was a sense of connectedness which participants felt when they were working together as a community, and a sense of wellbeing gained from eating what they perceived to be "healthy nutrient dense food" (OT8). Furthermore, there was a feeling of connectedness with nature when participants felt they were becoming more aware of the seasons through their involvement in the CSAs. It was common for participants to feel excited about what they may receive in their vegetable box each week. Over 90% of participants receive vegetables from the CSA that they would not normally buy or eat. Participants frequently said they wanted to avoid wasting the vegetables so they ate things they received that they otherwise would not have bought or eaten. CSA membership led to diversification of diets and increased value attributed to their vegetables, which was being produced on their behalf or in partnership with other CSA members.

4. Discussion

4.1. Health implications

Our research illustrates that there is an appetite amongst the UK population for changing diets, and it is possible to shift UK diets to better align with the EAT-Lancet dietary recommendations. The CSA group reflected current trends reported in recent consumer surveys that indicate that more people are adopting a flexitarian dietary pattern (Steenson and Buttriss, 2020; World Economic Forum, 2022), motivated by concerns about sustainability, animal welfare and health (Duckett et al., 2020). Nonetheless, even for the CSA diets, reductions are still needed in the consumption of tubers/starchy vegetables, dairy, beef/lamb/pork, eggs, and sugar; and increased consumption of wholegrains, legumes and nuts to align with EAT Lancet recommendations. Shifts in CSA members' diets will likely help to build resilience to nutrition-related non-communicable diseases such as Type II diabetes, cardiovascular disease and certain cancers, as well as potentially improving outcomes from infectious diseases. This has been highlighted through the COVID-19 pandemic, illustrated by the relationship between increasing obesity and poor disease outcomes (Public Health England, 2020; The Open Safely Collaborative et al., 2020).

4.2. Environmental implications

In addition to this, we measured CO2 emissions of foods consumed, and found lower emissions for the diets consumed by CSA participants compared to control group participants. Whilst our data analysis shows an average of almost ⅓ fewer CO2 emissions from dietary intake, we suggest that an overall reduction in environmental impacts may be larger, owing to the agroecological methods used in the production of the vegetables that CSA participants are consuming. Agroecological production practises rely on a largely closed system, where nutrients are recycled through the system, soil organic matter is promoted (which leads to higher soil carbon storage) and only local resources are used to promote productivity. In addition to very low to negative CO2 emissions, agroecology also promotes biodiversity both on the farm and in the surrounding ecosystems, generating multi-functional landscapes that are capable of supporting food production and biodiversity and are more resilient to both environmental and social shocks and stressors (Food Farming and Countryside Commission, 2021). Other sustainability impacts associated with CSA diets that should also be considered include: organic production of meat, eggs and fresh produce, eliminating the use of synthetic pesticides and fertilizers in production practises; and very low food miles and zero air miles used to transport food from farm to fork.

In this case, dietary changes to achieve either improved environmental sustainability or improved health outcomes are co-beneficial; i.e. a dietary shift for one reason or the other will achieve both benefits.

4.3. Accessibility implications

Considering further the question of affordability and cultural amenability of healthy and sustainable diets, prior to the COVID-19 pandemic in March 2020, in the UK, the rates of household food insecurity for households with children was already high, estimated at 11% of UK households (Sosenko et al., 2019). After the pandemic, this was estimated to have increased to 14% (Goudie and McIntyre, 2021), and further since the cost-of-living crisis, with current calculations of food insecurity in the UK at 20% (Armstrong et al., 2023). Similar increases in food insecurity have been experienced globally (World Bank, 2021). Austerity policies from 2010 to 2018 have been widely criticised as a driver for increased food insecurity and poverty in the UK (Alston, 2018), with approximately 20% of the population living below the poverty line (Social Metrics Commission, 2018). As has been reported in previous research (Galt et al., 2017), we found that CSA member households have higher than average income (see Table 1). Further research highlights that in the UK pre-pandemic, 26.9% of households would need to spend more than a quarter of their disposable income after housing costs to meet the costs of eating according to the Eatwell Guide (Scott et al., 2018). This is made worse by the cost-of-living crisis, where household disposable income will decrease by 7% over the two-year period between 2021 and 2023 (Office of Budget Responsibility, 2022). This raises a food justice issue, where a large

percent of the population is unable to afford a healthy diet. Given that our data indicated that the diets consumed by CSA members were lower in CO2 emissions than those consumed by control group participants, if these healthier diets are less affordable then environmental implications are also at stake. Widespread dietary change will remain elusive to a large proportion of the population, and therefore limits the scope for achieving net zero targets or improving resilience.

4.4. Policy implications

With this in mind, we suggest that approaches that would reduce the cost of a CSA diet for low-income and food-insecure households could be beneficial. Within the current UK policy context of the UK's withdrawal from the European Union, the UK government and the devolved governments (Scottish Parliament, Senedd Cymru and the Northern Ireland Assembly) are now in the process of implementing new agricultural policies. These are primarily based on the principle of paying public money for the provision of public goods, which holds that subsidy payments to farmers should be based on the provision of benefits such as better air and water quality, improved access to the countryside or measures to reduce flooding. This approach is similar to agricultural subsidy policies in the EU and Japan. Given that CSAs' production practises are based on agroecological principles, and indeed most CSAs are certified organic, these types of farming systems could benefit financially from such a policy approach and serve to achieve additional reductions in carbon emissions beyond that gained from changing consumption patterns. Here, we argue that public health is also a public good and should be recognised as such through receipt of additional subsidy payments for benefits rendered. In addition, food aid vouchers issued by local authorities could be used, for example by qualifying for double value when used for purchasing veg boxes, to support accessibility. Research by Bellmann (2019) indicates that payment transfers to consumers can play a significant role not only in ensuring food accessibility, but also in fostering healthy diets for food insecure households. Food aid vouchers specifically for vegetable consumption *via* small-scale horticulture farms would also serve to counteract the imbalance of commodity transfers for a small number of calorie-dense crops suited to large-scale industrial farming (three-quarters of total global commodity transfers by the 20 largest producing countries are for rice, maize, pig meat, beef and veal and milk, followed by wheat; Bellmann, 2019) and support reductions in global dependence on cereal crops that are relatively poor in nutrients; it further has the potential to increase demand for sustainably produced food.

Innovative social and solidarity economy approaches to food production and provisioning (Loh and Agyeman, 2019) can be another mechanism for reversing what can be viewed as exclusionary food practises, by engaging all households, regardless of income level, in healthy and sustainable food culture. Follow-on pilot research with food insecure households receiving a subsidised vegetable box indicates the important role of social capital at the community scale for generating healthy, sustainable and just outcomes for community-scale food systems (Verfuerth and Sanderson Bellamy, 2022). Social and solidarity economy is increasingly recognised by policy makers as a means for inclusive and sustainable development (Fonteneau et al., 2011; Mendell, 2014; Utting, 2017) and as a form of economy that is 'people-centred and planet-sensitive' (Zhongming et al., 2013). It has generated growing interest as a significant element in transformative change and achieving the United Nations Sustainable Development Goals.

Scotland's recent Good Food Nation Act illustrates political will to ensure that all people can afford a healthy and sustainable diet. The Food Policy Alliance Cymru (2021) has advocated for similar policy approaches in Wales where the Welsh Assembly is currently developing its Community Food Strategy and debating the Food (Wales) Bill. In England, the National Food Strategy (Dimbleby, 2021) advocates for community-based approaches to addressing healthy, sustainable and accessible diets. Common across these strategies is the recognition of the importance of community-scale approaches to achieving health, sustainability and accessibility objectives. There are opportunities in the legislative and policy spheres for change that could improve the accessibility of healthy diets and reduce GHGs. Our research suggests that accessible CSA models can play an important role in improving the health and sustainability of diets. Whilst this study shows the applicability of such an approach in the UK, it contributes to a body of literature illustrating such effects elsewhere, such as in the US, and contributes to a better understanding of how we might reorientate the food system to improve resilience for sustainable and healthy outcomes.

5. Conclusion

Our research illustrates that there is an appetite for changing diets, and it is possible to shift British diets to better align with the EAT-Lancet diet. We have addressed critiques in the literature that the EAT-Lancet diet is not appropriately tailored to the cultural context of different regions. Data from our CSA participants gives some indication of how British diets may be amenable to adhering more closely to the EAT-Lancet recommendations. However, significant changes are still required to align with international health and sustainability targets. Even for the CSA diets, reductions are still needed in consumption of tubers/starchy vegetables, dairy, beef/lamb /pork, eggs, and sugar; and increased consumption of wholegrains, legumes and nuts.

The data presented here is based on an initial study conducted to first understand if a CSA diet can deliver health and environmental sustainability benefits. Having found that it does, there are still several questions left to further investigate and answer. Principle amongst these is the question of motivation to change diets. Our research results show that households that join a CSA are motivated to make a change to the diet, often either for environmental sustainability or health reasons. However, further investigation is needed to understand whether the impact of a CSA diet can be extended to the rest of the population, which may not be motivated to make changes. We suggest exploring the dynamics of joining a CSA, which may serve to further inspire dietary changes; and researching the role that building relationships into the food system plays in motivating change. Policy approaches suggested herein will be required to support nations in generating more resilient consumption patterns that align with health, biodiversity, and zero-emission policy targets.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Cardiff University and University of the West of England. The patients/participants provided their written informed consent to participate in this study.

Author contributions

AB, EF, SM, AC, SF, EM, AM, and RS contributed to the project aims and objectives and the experimental design. AB and EF did data collection and analysis. AB, EF, and SM wrote the manuscript with significant input of ideas and edits from AC, SF, EM, AM, and RS. All authors contributed to the article and approved the submitted version.

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.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1160627/full#supplementary-material

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Political economy of protein transition: Battles of power, framings and narratives around a false wicked problem

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In this paper we revisit the current debate between red meat vs. alternative protein and explore the respective contribution that those two polarized discourses claim to make in relation to the new international agenda on transforming food systems toward a more sustainable future. To complete this, we combine classical political economy analysis focusing on the access and distribution of power and economic resources amongst different groups of actors, with a more sociological approach relying on discourses analysis. The first part of the paper highlights the relevance of adopting a political economy approach to explore the centrality of factors such as incumbent actors' powers and influence at both national and international levels. It also raises questions about the equitable redistribution of the dividends of the sector's rapid growth between the different groups of actors and in particular the marginalization of the smallholders. We then deconstruct some of the main narratives and counter-narratives that have emerged over the last two decades around the question of protein transition and show how those different narratives have been used as "discursive tools" by both the red meat and the alternative protein proponents to advance their own agendas and ignore others'. In doing so, we expose some of the unnecessary polarized or confrontational elements of the debate and suggest that the wicked nature of the problem as it appears at first sight may in fact be more the result of the framing used by particular actors, rather than the consequence of an irreconcilable tensions between diverging priorities.

KEYWORDS

food system transformation, political economy, protein transition, narrative analysis, discursive practices

Introduction—framing the problem

The term "protein transition" refers to the transition from a heavy red-meat consuming world to a more plant-based food system. The issue of transitioning away from red meat is a growing debate within the whole food system transformation literature, and a symbolic one (Purdy, 2020). In effect, along with sugar and salt, red meat (beef, pork, or lamb) is now often presented as an "unhealthy" food item when consumed in excess (Popkin, 2009; Vermeulen et al., 2020). In addition, the production and processing of animal-based proteins has also been recognized to be environmentally more harmful and resource intensive than plant-based sources (Herrero et al., 2016). The livestock sector is estimated to contribute 14.5% of our global GHG emissions (Gerber et al., 2013), and also, under some conditions, to increase land degradation, air and water pollution, and decline in biodiversity (Reynolds et al., 2010; Bellarby et al., 2013).

Yet, it is also well established that animal-based foods provide a concentrated source of vitamins and minerals (e.g., iron) that are particularly valuable to young children in low-income countries whose diet is otherwise generally poor (HLPE, 2017). Studies have demonstrated, for instance, large benefits from modest increases in meat in the diets of the poor in sub-Saharan Africa (Neumann et al., 2010). Conjointly, the livestock sector is also recognized to provide livelihoods to millions of smallholders (Steinfeld et al., 2006). Clearly, in some countries, *more* meat consumption, not less, would be beneficial to many.

The issue of protein transition seems therefore to involve conflicting and painful trade-offs between economic, ethical, societal and environmental objectives and priorities. As such it may look like a wicked problem. Not surprisingly, it has evolved over time in a heated argument between two coalitions of actors: on one side, the pro-livestock supporters who advocate for protecting the meat industry and its activities, and, on the other side, the pro-alternative-protein advocates who push for a replacement of red meat by other, more "sustainable" sources of protein.

The pro-livestock camp encompasses many different actors, including some academics and experts, but also—as expected—some of the largest transnational agri-food corporations (TNCs) such as JBS, Tyson Foods, Cargill and Smithfield -the world's four largest meat-producing corporations. These TNCs have invested billions of dollars in the sector and have very strong financial interests to ensure that the increase in the consumption of animal-sourced protein (including red meat) as it has been taking place in the last 40 years across the globe, continues in the near future. To some extent, the pro-livestock camp also includes the millions of smaller actors who livelihoods depend on livestock raising.

On the other side of the spectrum, an increasing number of international environmental or conservation organizations and global experts are now advocating for a drastic cut in the production and consumption of red meat. Applying the universal healthy reference diet advocated by the EAT-Lancet report would require, for instance, a more than 50% reduction in the global consumption of red meat -primarily by reducing excessive consumption in high-income countries (Willett et al., 2019). To substitute for red meat, alternative protein based systems[1] are being actively promoted in a growing number of countries, including Germany, South Korea, United Kingdom, or the Netherlands. In this last country for instance, several universities and think-tanks are heavily involved in the protein transition debate and are energetically pushing for the substitution to happen [e.g., NewForesight[2]; University of Delft[3]; Utrecht University,[4] Wageningen University,[5] the Green Protein Alliance,[6] and even the Dutch National Science Foundation (NWO)][7]. As such, the Netherlands could be seen as a likely precursor of a future stance amongst (high-income) countries in the emergence of alternative protein based national food systems.

At the present time, the international debate between pro-livestock and pro-alternative protein approaches seems to be deadlocked: no general consensus on how to address this thorny problem and to navigate the necessary trade-offs between human health, nutrition, economic and environmental impacts seems to emerge. The divide is very apparent amongst many different groups, including academics and experts, development practitioners, but also even amongst members of the same governments. For illustration, in 2021 the discord became evident between the Consumption Minister and the Prime Minister of Spain. The former (Alberto Garzón), being "worried about the health of [Spanish] citizens and the health of our planet", was forcefully advocating for a reduction of red meat consumption, while the Prime Minister (Pedro Sánchez), under pressure from the meat industry, openly opposed to the idea and the Ministry of Agriculture (Luis Planas) called Garzón's campaign "unfortunate" and "unfair"—pointing out that the meat industry in Spain produces one-fifth of the country's exports, worth 10 billion euros.[8]

Aware of these heated debates and acknowledging the pressing need to engage in a comprehensive transformation of our food systems (e.g., Béné et al., 2020; Webb et al., 2020), the objective of this paper is to revisit this debate and its apparent wicked nature from a political economy perspective. In light of the Spanish example above, one initial assumption is indeed that the concentration of a large share of the market power in the hands of a few national or international companies could influence or even limit the domestic policy space and the power of local and national governments. The fear is that some of the strong politico-economic dynamics that are already visible in the system at national or at global level (see e.g., Lundström, 2019) may contribute to "lock" this system further into its current trajectory and prevent or delay the structural transformation that is deemed necessary to achieve a long-term sustainability (Bernstein, 2016; IPES, 2017).

On the other hand, some would contend that reducing this debate to a traditional political-economy issue where power and status quo are in the hands of the most powerful players and framing it as a polarized debate between, on one side, the livestock proponents and, on the other side, the "alternative protein" (AP) proponents may, in itself, be part of the problem

1 Broadly defined, alternative protein refers to three types of products: (i) plant-based substitutes such as the 'Impossible Burger' or the egg substitutes made from algae-based powders, (ii) lab-grown meat/fish/dairy products and other novel manufactured high-protein foods, and (iii) insect-based protein products.

2 https://www.newforesight.com/frontrunnersfeatured/going-beyond-meat-accelerating-the-green-protein-transition-in-the-netherlands/

3 https://www.biotechcampusdelft.com/news-and-events/news/the-protein-transition-in-the-netherlands-alternative-proteins-that-can-act-as-substitutes-for-traditional-animalbased-food/

4 https://www.uu.nl/en/events/protein-transition-towards-sustainable-plant-based-diets

5 https://issuu.com/wageningenur/docs/ww2019_02_eng

6 http://greenproteinalliance.nl/

7 https://www.nwo.nl/en/funding/our-funding-instruments/nwa/transition-to-a-sustainable-food-system/transition-to-a-sustainable-food-system.html

8 https://www.wsls.com/news/world/2021/07/08/debate-over-eating-meat-gets-heated-in-spanish-politics/

-as this interpretation would undoubtedly reinforce, or at least contribute to, the perpetuation of this locked-in debate. The International Panel of Experts on Sustainable Food Systems (IPES) for instance, posits in their report on the Politics of protein: "At a critical juncture for food systems reform, the proliferation of competing claims in the "protein debate" is exacerbating tensions and creating further polarization—between animal welfare activists and livestock farmers; environmental and anti-poverty organizations; urban and rural populations; and between meat-eaters, vegetarians, and vegans" (IPES, 2022, p. 16, our emphasis).

Navigating between those two positions, the premise of this paper is that, when it comes to food and especially red meat, it is not just about the interests of the private sector (with power, connections and money) *vs*. considerations of public health or environmental conservation, even if (as we shall see below) those two are critical components of the same equation. Instead, as we intend to demonstrate in the rest of this paper, a more appropriate way to comprehend this problem is to adopt a more nuanced interpretation of the current discourses and narratives contributing to this apparent lock-in. We will argue in particular that unpacking carefully the different arguments, discourses, narrative and counter-narratives (Roe, 1994; Keller, 2020) adopted by the main actors, and critically analyzing the "framing" (van Hulst and Yanow, 2016) that these different actors (sometimes unconsciously but also often intentionally) use to define the problem, can be a first important step to disentangle, explain and hopefully ease some of the tensions that are currently observed and that are contributing to the polarized nature of the debate around protein transition.

When using the term "framing" in this paper, we refer to the concept initially developed by van Hulst and Yanow (2016) in relation to public policy and now more broadly used in social theory (Badie et al., 2011) to describe the interactive process by which decision-makers or actors build narratives to explain or justify decisions. More specifically, in the context of this paper, framing will be used to emphasize the politically constructed nature of the "stories" around protein transition.

Against this background the rest of the paper is organized as follows: first, we review some of the main elements which have led a growing number of scholars to argue that political economy is a relevant framework for the analysis of the protein transition and more globally of the food system transformation (Béné et al., 2020). Although only based on a succinct review, our intention is to demonstrate that this political economy approach is indeed legitimate when it comes to analyzing the meat transition as it helps demonstrate the centrality of elements such as powers and influence (of the incumbent actors) in explaining the current situation. In a second part, we complement this initial political economy 'glance' with an analysis focused on discourses—what could be called discursive political economy. The intention, in that second part, is to 'deconstruct' some of the narratives and counter-narratives that have been adopted by the different protagonists of the debate, and to reveal how those narratives -often carefully framed around a particular vision or interpretation of the problem- contribute actively -and sometimes intentionally—to the contested nature of the debate. As such, we argue, those polarized discourses are part of the problem.

Finally, although the constellation of actors involved on both sides of the debate is large and diversified—including experts and academics, policy-makers, civil society, as well as private sector (from small local artisanal enterprises or even start-ups to multi-billion dollar agri-food TNCs)—we propose to focus our attention mainly on the first of those groups, the experts and academics, because of the special responsibility that this group has in relation to the generation of knowledge, which puts them in a privileged and powerful position vis a vis the rest of society.

The old and new political economy of the protein transition

Central to the contemporary conceptualization of political economy is the question of power, considered in all its forms and expressions, spanning from politics and economics to finance, of course (Weingast and Wittman, 2008) but also, more subtly, to discursive practices, social norms, or discourses (Foucault, 1983; Krzyzanowski, 2020). Applying a political economy lens to a given sector (e.g., energy, health, etc.) can therefore help identify why and how particular status quo or practices persist despite a growing call for transitions. It also draws attention to the winners and losers of those practices.

In the past, political economy has been used in the context of food systems in general (e.g., Friedmann, 2005; Pritchard et al., 2016); and, today, it continues to be called upon to shine light on some of the current or emerging issues, especially around food system dynamics and systemic lock-ins, or the issue of inequality in power and decision making (e.g., IPES, 2015; Leach et al., 2020). IPES (2015, p. 5), for instance, remarks: "power imbalances, often stemming from economic inequalities, are a key factor in the way food systems operate". The specific case of the meat industry does not seem to differ significantly from this general statement (Williams, 1999). In fact, many would even argue that the meat industry is one of the major agri-food sectors where this sense of power imbalance is the strongest (Winders and Ransom, 2019).

What do the facts tell us?

The value of global meat production had increased from about $65 billion in 1961 to $366 billion in 2014 (in constant 2004–2006 US$)—an increase of more than 500% (FAO, 2019). This economic value, however, is not spread evenly among farmers, workers, and corporations, or even between countries. Rather, this massive increase in meat production has mainly benefitted big international corporations in the Global North and in some large industrializing countries (specifically, Brazil and China). A handful of those corporations (such as JBS in Brazil, WH Group in China, and Tyson in the US) have come to dominate the meat industry as it expanded over the past five decades. These TNCs do not simply control the production, but also the required inputs (upstream sector) and the processing of meat products (downstream activities). For instance, Cargill, headquartered in the US and one of the world's leading grain traders, is also the second-largest animal feed manufacturer and the third-largest meat processor in the world.

Importantly, each of these TNCs has not just benefited from the worldwide exponential increase in meat demand; they also benefited from substantial help from their respective governments. In the US, for instance, Tyson received a diverse array of subsidies, among which the most important was aimed to reduce the costs of corn and soybeans used to feed livestock. Starmer et al. (2006) estimated that, between 1997 to 2005, through direct subsidies provided by various US Department of Agriculture's (USDA) programs, Tyson managed to save an estimated US$288 million per year (Starmer et al., 2006), while Smithfield -another major agri-food firm involved in pork production and processing- saved the equivalent of US$284 million per year for the same period (Starmer and Wise, 2007).

In China, the pork industry has also received massive support from both central and provincial governments (Schneider, 2017). For instance, in 2013 when the WH group acquired Smithfield—thus *de facto* becoming the world's largest pork processor-, the transaction was made possible thanks to a $4 billion loan provided by the Bank of China as part of the wider Chinese central government strategy to boost the capacity of the national pork industry (Howard, 2016). When other aspects of production (including grants, subsidized loans, and tax breaks) are accounted for, the pork industry in China has been receiving an estimated US$22 billion during the early 2010s, which would represent the equivalent of a US$47 subsidy per pig (The Economist, 2014—reported in Howard, 2016).

A similar pattern is observed in Brazil. There, Pigatto and Pigatto (2015) described how JBS—which is now the world's largest meat processor of beef, pork and poultry—benefited from substantial financial supports through federal feed subsidies as well as very advantageous low-cost loans, in exchange for letting the Federal Government become a shareholder of JBS. These "arrangements" were part of Brazil's "national champions development strategy", whereby the Brazilian government invested in some of the largest national firms, and particularly in the meat sector, because of their world-leading position in international trade.

Howard (2016) and Schneider (2017) provide detailed accounts of those various interferences of national/federal governments in the economics and finance of the "Big Meat" industry. They show how the financial interests and political agenda of those governments have become so entangled with those of the industry that it is now very difficult for those governments to reverse the tide and engage in the types of drastic policy changes that would be necessary to maintain the global food system within planetary boundaries (Béné, 2022).

The other side of the red meat equation

Another piece of the puzzle in this initial political economy analysis rests with the fate of other main actors, those millions of smallholders whose livelihoods depend for a great extent on raising livestock and who were expected to benefit from the so-called "Livestock revolution".

The term Livestock Revolution was initially coined by Chris Delgado and his colleagues in a IFPRI discussion paper (Delgado et al., 1999), possibly with the intention to highlight some parallel with the Green Revolution and the poverty alleviation outcomes it delivered to rural/agrarian populations in Asia and Latin America during the 1960s and 1970s (Raj, 2013). By framing this Livestock Revolution as "the next food revolution" (the title of Delgado's paper), those authors were indeed referring to the assumption that this new "revolution" would generate economic opportunities for small-scale farmers in low- and middle-income countries (LMICs). The underlying argument was that although the bulk of the benefits may still be captured by the large agri-food companies through the wide-ranging vertical integration process that has characterized the sector in the last 20 years, the 'rising tide' would also benefit resource-poor smaller-scale farmers (see also ILRI, 2002 or Nin et al., 2007). In theory, those smaller-scale farmers were expected to cash in some of the trickle-down benefits of the revolution (Brown, 2003; Global Livestock Advocacy for Development GLAD, 2018) by getting access to previously unreachable global markets through their 'partnership' with the larger agri-food companies (Waldron et al., 2003).

What empirical data reveals, however, is that for the majority of the small-scale farmers living in LMICs, this livestock revolution did not materialize (Dijkman, 2009; Narrod et al., 2010; Pica-Ciamarra and Otte, 2011). Instead, the "red meat revolution" involved a process of vertical integration by which small actors became highly dependent on larger agri-food companies (see, e.g., Khan and Bidabadi, 2004; Gura, 2008). Because this vertical integration also implied a rigid adoption of more capital-intensive technologies (Nin et al., 2007), smallholders were generally unable to afford the required technical upgrading, exposing them to risks of severe indebtedness (von Kaufmann and Fitzhugh, 2005). In the view of many, the vertical integration that was presented initially as the motor of the Livestock Revolution eventually disempowered and marginalized small-scale farmers as opposed to empowering them (Dijkman, 2009; Pica-Ciamarra and Otte, 2011).

What about the alternative protein movement?

It would be wrong to assume that the concentration of power, resources and influence as described above only applies to the red meat industry. Although the perception we have of the alternative protein world is often one of myriad 'smart' disruptive start-ups wrestling to create a little space for their own original innovation, the reality is quite different. What emerges from the most recent analyses (see, e.g., Clapp and Scrinis, 2017; Mouat et al., 2019; Howard et al., 2021) is, on the contrary, a world where the research and development (R&D) of those alternative protein products is now essentially controlled by the same TNCs that have been leading the meat industry for the last three to four decades. In the last few years, Cargill, for instance, invested in the lab grown meat company Aleph Farms, join ventured with the pea protein firm Puris, and later introduced its own plant-based meat substitute; JBS purchased Bio.Tech.Foods (a Spanish lab grown meat firm) in 2022 while investing another US$100M in developing lab grown meat (IPES, 2022). Other major agri-food TNCs who invested in alternative protein include Nestle who acquired Sweet Earth in

2017, Unilever who acquired The Vegetarian Butcher in 2018, Kerry Group who acquired a majority stake in Ojah (a Dutch company specialized in the production of plant-based ingredients), or Hormel who acquired Skippy and Justin's, two peanut firms, in 2016 (Howard et al., 2021). Not to forget McDonald of course who ventured with Beyond Meat to develop their "McPlant" plant-based patty. In sum, nearly all the largest meat and dairy TNCs as well as some of the largest fast-food corporations have, in recent years, invested massively to acquire existing plant-based substitutes or to develop their own.[9] The reason for these investments is obvious. The meat substitute market is expected to reach annual sales of US$12 billion by 2025 and $17 billion by 2027, with an annual growth rate of 15–18% projected from 2020 to 2025 (Meticulous Research, 2020). Europe is currently the largest market for these products with the popularity of meat analogs among consumers seeking protein alternatives and sustainable food particularly high in Germany, France, the Netherlands, the United Kingdom, Italy, and Sweden -even if Asia is currently estimated to be the fastest growing market (Mordor Intelligence, 2020, cited in Howard et al., 2021).

In sum the image of the small, smart and friendly start-ups striving to find a solution to the unsustainability of our food systems and to improve the health of the planet by developing less harmful and more environmentally or animal-friendly products needs to be replaced by the cold reality of a growing market, worth billions of dollars, being appropriated and now almost entirely controlled by some of the largest corporations of the global food system.

Overall, what this first part of the paper reveals is that the meat industry in both high- and lower-income countries, is rapidly changing, but perhaps more importantly, that those changes have been driven -and continue to be driven- by markets forces and powerful actors. As such this overview confirms the idea that a political economy lens is relevant to analyze not only the current structure but also the dynamics of the changes that have characterized the meat industry in the last two decades.

Protein transition: wicked problem or strawman argument?

Wicked problems are generally understood as issues or problems that are difficult or impossible to solve because of some element of dilemma and/or internal conflicting objectives. In planning and policy literature, the expression refers to debates that are socially and/or politically complicated because of incomplete, contradictory, and changing conditions (APSC, 2007). As (Head and Alford, 2015, p. 712) remark, for those reasons, "wicked problems seem incomprehensible and resistant to solution".

At first sight, the red meat transition does look like one of those wicked problems: as recalled in the introduction, red meat has now been recognized to be a major contributor of climate change as well as a main source of land and environmental degradation (Gerber et al., 2013; Willett et al., 2019; Ranganathan et al. 2016). In addition, when consumed in excess, red meat has also been recognized to contribute to serious public health problems, including increased risks of stroke, type-2 diabetes, some forms of cancers and cardiovascular diseases (Etemadi et al., 2017; Zeraatkar et al., 2019). Yet, red meat and animal-source foods more generally provide a concentrated source of some of the critical vitamins and minerals necessary for young children's physical and cognitive development, as well as for pregnant and lactating women, and more generally people suffering from undernutrition (Mozaffarian, 2016; HLPE, 2017). Therefore, many experts insist of the need to boost animal-source foods consumption in regions where diets are otherwise poor, such in sub-Saharan Africa and some parts of South Asia (Gibson, 2011). In addition, livestock contributes to the food and nutrition security of millions of poor smallholders in those same countries, directly through the consumption of their own animals and indirectly from the incomes that they derive from raising and selling those animals.

Framed as such, the tension between two conflicting objectives; on one hand, the need to drastically reduce global production and consumption of red meat to remain within planetary boundaries and to address the red meat health crisis, and, on the other hand, the necessity to increase and facilitate the consumption of animal-source food in some particular parts of the world or for some particular groups, could be seen as the root of an irreconcilable dilemma between two incompatible priorities, making it look like a wicked problem.

The (deceptive/fallacious?) wicked nature of the problem

We argue however that part of this apparent wicked problem is simply the result of a 'battle' of narratives and counter-narratives in which the pro-meat on one side and pro-alternative protein on the other, quarrel with each other, creating a confrontational discursive battlefield where the strategy is not to describe reality as it is (i.e., complex, nuanced and often ambivalent), but rather to present the problem in such a way that one's view/interpretation would be embraced by the largest number, even if achieving this implies deploying deceptive or fallacious arguments. In some other cases, the arguments may be valid but the way the problem is 'framed' is partial or biased, preventing the emergence of the full and comprehensive picture. As such, we argue, those narratives contribute to create or to reinforce the wickedness element of the debate, as opposed to address it.

Narratives and counter-narratives

Understood in a relatively 'generic' manner, a narrative can be seen as a storyline (Roe, 1994) used to explain or interpret reality as we observe it. Decision-makers, stakeholders or even researchers and experts adopt such storylines to define what a given problem is (and what it is not) and identify the solution they see appropriate or necessary to address that problem (Yanow, 1996; Drysek, 1997). Narratives can therefore become discursive 'tools' used to justify or impose specific policies, official positions, or even research agendas.

9 Other major influential investors including multi-billionaires such as Richard Branson or Bill Gates who advocate for lab-grown 100% synthetic beef substituting for animal-based protein (Temple, 2021).

Applied to the question of the (un)sustainability of our food systems, narrative analysis has already shown to be useful in revealing how different views and interpretations prevail amongst experts about the nature of the "sustainability crisis", and consequently about the types of solutions that are needed to fix the problem (Béné et al., 2019). In the present case, we propose to use more specific examples to illustrate how such narrative analysis can help unpack the stories behind the protein transition and debunk some of the contested elements of the problem.

Let us first briefly illustrate how important the *framing* of a problem -or of a solution- is for its perception and potential acceptability by the general public. In a recent analysis, Bryant and Dillard (2019) explored the level of consumers' acceptance for what is called "cultured meat" (i.e., meat grown *in-vitro* in laboratory). For this, they proposed to present this new product using three alternative narratives: (i) "societal benefits", (ii) "high tech", and (iii) "same meat". The first narrative, advocating for societal benefits, presents cultured meat as "clean meat [that] has many benefits for society like reducing harm to the environment and helping animals"; the second narrative ("high tech") presents cultured meat as "clean meat (…) made using highly advanced technology in a state of the art laboratory"; and the third narrative ("same meat") presents cultured meat as "clean meat [that] tastes like conventional meat, is increasingly affordable and can be healthier to eat" (Bryant and Dillard, 2019, p. 3). Bryant and Dillard then show that when introduced to the general public (in their case, a group of US adults), the level of acceptance of the product depends highly on the initial framing used. In particular, the "high tech" narrative received significantly less support and was less likely to be widely accepted, compared to the two other narratives,[10] even though the product it was advocating for was exactly the same.

Interestingly, livestock proponents also use this apparent skepticism about the "high-tech" narrative as part of their strategy to fight the rise of alternative protein (AP). A series of counter-narratives were developed recently by those livestock proponents with the aim to contest the different narratives that AP supporters have developed. In a very insightful analysis, Sexton et al. (2019) dissect several of these counter-narratives. The first is the "Frankenfood" counter-narrative, which builds on the consumers' hesitance regarding the technoscientific methods used to produce these alternative products, spreads doubt about the technological capabilities of the new AP companies to produce competitive and quality products. In parallel, another powerful counter-narrative emphasizes the "ultra-processed" nature of alternative meat. This second counter-narrative builds on the apparent contradiction between, on one hand, the claims made by AP proponents that alternative proteins are more environment-friendly than conventional meat production and, on the other hand, the fact that those alternative meats are in reality ultra-processed food- which is, everything but "natural".

At the end, both the narratives put forward by AP advocates and the counter-narratives developed by the livestock proponents create a very polarized landscape between two divergent interpretations about what "qualifies" as meat and what a better or healthier protein-food system should look like. As concluded by Sexton et al. (2019), this narrative-counternarrative battle feeds from a combination of individual and collective societal concerns or fears regarding the welfare of people, animals and the planet, both in the present day and in the future, as well as elements related to the cultural, social and ethical values associated with animal-based foods. To some extent, they both draw from the same initial collection of values and concerns; yet, end up proposing completely opposed 'solutions'.

As we shall see below, these debates also touch upon the interaction between ontology and epistemology and the role that science, knowledge and expertise play in creating, maintaining or in some cases exacerbating those contested narratives through what would be considered discursive practices. The term "discursive practices"—understood here in a Foucauldian sense (Foucault, 1983)—refers to practices of knowledge construction and assertion and intend to describe how specific knowledges ("discourses") operate and what discursive outcomes they eventually aim to achieve. Put simply, discursive practices are the *practices of discourses* (Bacchi and Bonham, 2014, p. 173) and their analysis can be very instructive.

Discursive practices around protein transition

In this section we review examples of discursive practices used by scientists, experts or private sector actors as part of their effort to influence the red meat *vs*. alternative protein debate. Those examples are listed in Table 1 and discussed in greater detail below.

A first discursive strategy, used almost universally, consists in constructing the core of a given argument around the strengths and advantages of its specific content -and to forget or omit the limitations and negative elements or trade-offs that it may also imply. To a large extent, this corresponds to the conventional way the literature understands the concept of frame:

> "Frames highlight certain aspects of a situation and obscure others, in order to define problems, diagnose causes, make moral judgments and suggest remedies (…). As such, frames determine what the actors (…) will consider relevant or important and how the definition of competing problems lead to normative prescriptions for action" (Béné et al., 2021, p. 989).

In the context of the AP debate, a first example of this discursive strategy is when experts (correctly and rightly) point at the multiple health benefits that moderate consumption of (red) meat can bring, especially to people at risk of micro-nutrient deficiencies, but at the same time downplay, or neglect to mention, the negative consequence of consuming too much meat. Adesogan and his colleagues, for instance, made the point that:

> "Compared to plant foods, ASF [Animal Sourced Foods] supply greater quantities of higher quality protein and more bioavailable vitamin A, vitamin D3, iron, iodine, zinc, calcium, folic acid and key essential fatty acids. (…) In addition, ASF are the only natural source of vitamin B12, the deficiency of which

10 The "same meat" framing was shown to be conducive to the most positive attitudes amongst those adults (Bryant and Dillard, 2019, p. 6).

TABLE 1 Example of practices found in various discourses in relation to the debate on protein transition.

Discursive practices	Examples amongst	
	Livestock proponents	Alternative protein proponents
Systematic omission of the 'negative' element of an argument—only the strengths and advantages are presented, omitting the other (more problematic) aspects of the proposed 'solutions'	Adesogan et al. (2020), when they omit the health and environmental impact of red meat production/consumption	Patrick Brown, CEO of "Impossible Foods" when he omits the lower-than-expected environmental gains of alternative protein solutions
Use of incorrect or incomplete data or information	Livestock Global Alliance [LGA] (2016), when they claim that livestock contributes 40% of the agricultural GDP in developing countries	Willett et al. (2019), when they claim that healthier diet would lead to a reduction of 11 million premature deaths, conflating correlations with causality
Use of fallacious *argumentum ad hominem*–trying to win an argument by challenging one's opponent's knowledge or questioning their (scientific) integrity	R. Petre, Executive Director of the "Global Roundtable for Sustainable Beef", when he denigrates the FAO "*Livestock's Long Shadow*" for ignoring or deliberately minimizing the contribution of the livestock sector	Goodland and Anhang (2009), when they criticize the same FAO *Livestock's Long Shadow* report for being inaccurate and biased in favor of the livestock sector

> is associated with developmental disorders, anemia, poorer cognitive function, and lower motor development" (Adesogan et al., 2020, p. 2).

They then concluded:

> "To this end, increasing access to and consumption of moderate amounts of ASF should simultaneously be a global priority for people in areas where undernutrition remains a persistent problem, particularly for infants and women of childbearing age." (Adesogan et al., 2020, p. 3–their emphasis).

All the information provided by those authors is correct and they offered several references to back-up their statements. What they omit to mention, however, is that excessive consumption of red meat has also been documented to increase the risks of serious health complications -see our succinct summary above—and that those diet-related health problems are responsible for more deaths than any other risk factor in the world (Afshin et al., 2019). They also omit the many environmental impacts associated with the red meat industry. Instead, they made the following two statements:

> "Animal source food production contributes meaningfully to goals for a sustainable food system by converting millions of tons of agro-industrial by-products that cannot be consumed by humans into livestock feeds, concomitantly reducing waste and environmental pollution and increasing human-consumable food" (Adesogan et al., 2020, p. 4–our emphasis).
>
> "Sustainable intensification of livestock production, which involves improved resource use efficiency with environmental stewardship can foster a reduction of greenhouse gas emissions" (Adesogan et al., 2020, p. 4–our emphasis).

The authors did not provide references, however, for any of those statements. In essence, what we observe here is a first vivid example of discursive practices, performed by scientists.

On the other side of the debate, plant-based meat proxies and meat alternatives from various animal and novel sources (e.g., insects, cultured meat, algae) are often presented by AP supporters as a promising industry that has attracted multibillion-dollar investments over the last decade and is said to offer "plausible and desirable futures" (Bai et al., 2016; Tziva et al., 2019). According to this literature, environmental, human health and animal welfare concerns are the main factors that have driven the development of those different meat alternatives. As part of this discourse, those AP products are presented as the solution to "the inefficiencies of the meat production (…) [and] the negative impacts from the consumption of meat on human health and the environment" (He et al., 2020, p. 2639). Overall, the main narrative is one where red meat is to be replaced by something cleaner, healthier, and more environmentally friendly, in one word, something "better"; and the role of technological innovation in this sustainable and healthy transition is often viewed as instrumental (Herrero et al., 2020). For instance, the trademark of DSM, one of the lead actors in this vibrant alternative meat industry, is "Bright science, brighter living". [11] Likewise, Patrick Brown, CEO of 'Impossible Foods' founded in 2011, is keen to contrast "meat today [that] is basically made using pre-historic technology"[12] with the molecular engineering technique that his company uses to create plant-based burgers.

In sum, in order to boost consumer demand and secure investments, AP proponents offer a series of "promises" that are framed to feed the imagination of the consumers (Stephens, 2013). What these different narratives don't mention, however, is that the potential sustainability gains of those disruptive and high-tech options may turn out to be much lower than expected or claimed (van der Weele et al., 2019). While comparing the technical feasibility and production costs of different alternatives, several recent studies concluded that even though those alternative solutions may be technically feasible, their potential environmental gains are more limited than their advocates claim (see, e.g., Tuomisto and Teixeira de Mattos, 2011; Alexander et al., 2017; van der Weele et al., 2019). Part of the reason for this limited gain is the extensive processing that they generally require and the high energy consumption and subsequent losses during the transformation from raw material into final products.

Omitting part of the reality is thus a strategy frequently adopted by parties on both side in this debate. This is not, however, the only

11 https://www.dsm.com/food-specialties/en_US/markets/savory/plant-based-meat-alternatives.html

12 Quoted in 'Our Meatless Future: How The $2.7T Global Meat Market Gets Disrupted'. (Aug. 2021) https://www.cbinsights.com/research/future-of-meat-industrial-farming/.

strategy adopted as part of those discursive practices. Another way to try and slant the discussion is to build (part) of the narrative on incorrect information. For instance, it is often (correctly) argued that raising livestock is a critical part of the livelihoods of many poor people, most of whom live in low or even middle-income countries. As part of this narrative, the figure of 40% of agriculture GDP being tied to the livestock sector is frequently quoted. For instance, the Livestock Global Alliance state:

> Livestock is the fastest growing agricultural sub-sector today, making up five of the six highest value commodities in the world and 40 percent of agricultural Gross Domestic Product (GDP) in developing nations (Livestock Global Alliance [LGA], 2016, p. 1–our emphasis).

Beyond the fact that the world's fastest growing agriculture subsector is not livestock as claimed here, but aquaculture (which is often included in the wider livestock sector) (HLPE, 2014; Béné et al., 2015), we draw the attention of the readers to the "*in developing nations*" at the end of the LGA's statement. The problem is that this statement is incorrect. Salmon (2016) clarifies this point:

> "Globally, 40% is a figure regularly quoted as being the contribution that livestock makes to total agricultural production, in terms of gross domestic product (GDP). [This] 40% figure appears to originate from calculations made by Steinfeld and co-authors in the "Livestock's Long Shadow" publication (Steinfeld et al., 2006). (…) A recalculation for years 2005 to 2014 (…) demonstrated that although there has been variation in livestock's contribution to agricultural GDP, the global average remains around 40%. (…) However, the global figure obscures significant variations by region. Notably, LMICs have a substantially lower proportion of total agricultural GDP coming from livestock" (Salmon, 2016, p. 1—our emphasis).

In effect, for LMICs, the contribution of livestock to GDP is between 20 and 25%, not 40%—see figure in Salmon 2016 based on updated FAOSTAT and World Bank data. So, deliberate omission or honest oversight from the LGA? Difficult to know. The point is that all those who continue to refer to that 40% figure (see, e.g., Adesogan et al., 2020; World Bank, 2022) contribute to create—or to maintain—a false image about the importance of livestock in the economy of LMICs—at least when measured in terms of GDP. A more appropriate indicator would probably be the number of households whose livelihood and/or food security is partially dependent on livestock—see Salmon et al. (2020)'s more recent paper on this issue.

Similarly, proponents of AP also appear to be tempted to use false or biased statements in their attempt to influence the discussion. For instance, Solar Foods who developed a bacteria-based protein powder (called Solein) claimed that it is "100 times more efficient in converting energy to calories than animals" (Solar Foods, 2021). Yet, as pointed by IPES (2022), there does not appear to be any publicly available data to substantiate this claim.

What also emerges from the literature is the voluntarily amalgam between simple statistical correlation and causality, as a way to build or support specific narratives. In our case, while many scientifically rigorous studies which found statistical associations between consumption of red meat and high prevalence of cardiovascular and other non-communicable diseases (NCDs) were generally relatively careful not to overinterpret their results, subsequent scientific analyses which build on those initial findings may have been less rigorous and ended up making some questionable causality inferences. One of the most recent examples of this is the EAT Lancet report which relied on the confirmed association between high consumption of red meat and NCDs to claim that "Dietary changes from current diets to healthy diets are likely to substantially benefit human health, averting about 10·8–11·6 million deaths per year" (Willett et al., 2019, p. 448—our emphasis). While there is little doubt that the adoption of healthier diets -and in particular the reduction of red meat consumption by those who overconsume it- would lead to a reduction in the number of premature deaths, the statement made by the EAT Lancet report (and the figure behind it) is built on that fuzzy amalgam between association and causality.

Another strategy widely used to try to influence a debate is to make the opponents look biased or untrustworthy, by challenging their knowledge or even questioning their (scientific) integrity. In the linguistic literature this is what is called a fallacious *argumentum ad hominem*, that is, a rhetorical strategy where one side would challenge the agenda, motive, or some other attributes or features of the other side rather than contesting the substance of the argument itself (Tindale, 2007). One example of this strategy can be found in Goodland and Anhang (2009) where those two authors criticize the FAO report *Livestock's Long Shadow* (Steinfeld et al., 2006) as being too lenient with the meat industry and in particular too conservative in their estimate of the impact of livestock on climate change. In their 10-page paper, Goodland and Anhang use the terms "undercounting/ted"; "underestimated"; "understate"; "overlooked"; "imprecision"; "did not account for" or "flawed/wrong" 22 times, essentially to delegitimize Steinfeld and his colleagues' work and to argue that "these [pieces of evidence] are obvious but underestimated, some are simply overlooked, and some are emissions sources that are already counted but have been assigned to the wrong sectors (Goodland and Anhang, 2009, p. 11). Ironically, Steinfeld's *Livestock's Long Shadow* report has also been heavily criticized by experts from the other side (the livestock proponents), but this time for being too disparaging of the sector. Adesogan et al. (2020), for instance, refer to "narrow interpretation", "negative perceptions", and "overestimation of the environmental footprint". Subsequently, TNCs and individual private sector actors in support of the livestock industry also adopted this *argumentum* strategy by actively denigrating the AP narrative and anyone who seemed too critical of the livestock sector. R. Petre, Executive Director of the "Global Roundtable for Sustainable Beef" declared for instance:

> "While we have long recognized the challenges that face the livestock sector, these seem to be amplified in the echo chamber of modern media, while many very significant contributions livestock make to livelihoods and food production systems are either ignored or deliberately minimized."[13]

13 https://wa.grsbeef.org/resources/EmailTemplates/Archives%20Connect/2018/071718/index.html

Others go even one step further and are not afraid of comparing discourses supporting vegetarianism and veganism with "colonialist thinking" biased toward a "Euro-centric perspective".[14]

Returning to the *Livestock's Long Shadow* report and the instrumentalization of its conclusions, it is worth noting that the Steinfeld report is now recognized to have played a pivotal role in raising the awareness of the general public about the link between livestock, climate change and environmental degradation (Salmon et al., 2020). In the Netherlands for instance, the publication of the report was used by several political parties and societal organizations to justify their own positions regarding the unsustainability of meat production. Coupled with the introduction of the political "Party for the Animals" and the release of the documentary "Meat the Truth" in 2007 (NGPF, 2019), meat production and consumption has become a highly debated issue in the Netherlands (Tziva et al., 2019).

In sum, what we see emerging are assemblages of contentious and divergent constructions of the same reality, interpreted and (more importantly) communicated, in the form of deeply entrenched and polarizing discourses by different actors with specific agendas. Analyzed from a wider perspective, those examples are powerful illustrations of how research and researchers can fail to provide the right support to untangle a societal debate and instead contribute to, or get caught up in, what we refer as the "politicization of science" (Béné, 2022)[15]. In this politicization process, contests are thus not just about the role of technology, markets or the state—as a more conventional political economy analysis would suggest (e.g., Khan and Bidabadi, 2004; Bernstein, 2016; De Schutter, 2019) —but also about the construction of the knowledge underpinning them (Parkhurst, 2017; Leach et al., 2020). In this sense, the science that is invoked to legitimize (or delegitimize) calls for the protein transition is also an arena of political contestation. It does not provide neutral value-free guidance as to what is to be done, how, and by whom. Instead, it contributes -and this is the main argument of this paper—to the current polarization of the debate.

Conclusion

There is little doubt that a form of political contestation has emerged in the current scientific and societal debates about protein transition and the role of livestock in building a new, sustainable, food system (Kanerva, 2021). This observation should not come as a surprise. As Parkhurst (2017) and many other sociologists before him reminded us, social norms, ideologies, personal agendas and power relations can be central elements in the creation of knowledge (e.g., Longhurst, 1989), leading Krieger to consider scientific data not just as a neutral instrument supporting decision-making but as a "social product" (Krieger, 1992, p. 413) used to influence and shape how problems are perceived.

In this paper we revisit the current debate between red meat *vs.* alternative protein and explore the respective contribution that those two polarized visions claim to make in relation to the new international discourse on transforming food systems toward a more sustainable future (Caron et al., 2018; Webb et al., 2020).

The starting point of the discussion was the apparent wicked nature of the problem between, on one hand, the need to drastically reduce the global production and consumption of red and processed meat (Popkin, 2009; Ranganathan et al., 2016; Willett et al., 2019), and on the other hand, the need to boost the level of protein in the diets of particular populations at risk of undernutrition (Neumann et al., 2010; HLPE, 2017), as well as protect the livelihoods of the millions of livestock-raising households in LMICs.

We started the analysis by highlighting why adopting a political economy approach is relevant in relation to the meat industry, especially to analyze not only the concentration of power in the hands of the "Big Meat" sector but also the role that the governments of specific countries have played to contributing to this highly inequal system. In parallel we recall that a substantial number of analyses challenges the claim that the Livestock Revolution has been an effective pathway out of poverty for smallholders (Narrod et al., 2010; Pica-Ciamarra and Otte, 2011). Pushing this first conclusion one step further, it means that the argument that a reduction of the global production and consumption of red meat may harm poor smallholders is a false argument since those smallholders are not benefitting from the red meat revolution in its current form. Instead, what we saw is that the rapid growth of the sector led to further vertical concentration of power and resources in the hands of fewer actors (essentially a dozen TNCs operating from the global North but also Brazil and China) and that this process of concentration was facilitated by the close economic and financial ties that those TNCs have developed with the governments of those countries (Howard, 2016; Lundström, 2019).

To some extent, those findings are not completely new, nor surprising. They confirm in the specific case of the red meat industry what has been observed more globally for the whole food system, that is, the extremely high level of concentration of power, influence and resource in the hands of a very limited number of actors, mainly a handful of TNCs (Khan and Bidabadi, 2004; Bernstein, 2016; Howard, 2016; Clapp, 2021; Béné, 2022). What is perhaps more surprising -and certainly new- is that those powerful actors are also the ones who are now in full control of the AP sector, having co-opted or bought one by one all the AP start-ups which emerged in the last 10 years. In sum, the dream of some to see the Big Meat industry being challenged and the current status quo being disrupted by those new-comers has died even before the protein transition was completed.

14 Sarah Taber, reported in https://qz.com/1311884/is-promoting-vegetarianism-a-form-of-colonialism/.

15 Politicisation of science denotes the process by which specific pieces of evidence or academic works are cherry-picked—or on the contrary ignored or hidden—as a way to advance particular agendas, ideologies or ideas (Parkhurst, 2017).

In the second part of the paper, we complemented this initial political economy assessment with some element of critical discourse analysis (Weiss and Wodak, 2003; Keller, 2020). For this, we deconstructed some of the main narratives and counter-narratives that have emerged over the last two decades around the question of protein transition and showed how those different narratives have been used as "discursive tools" to advance particular agendas and ignore others. In doing so, we exposed some of the unnecessary polarized or confrontational elements of the debate, which suggests that the wicked nature of the problem as it appears at first sight may in fact be more the result of the framing used by particular actors, rather than the consequence of an irreconcilable tensions between diverging priorities. In other words, the wickedness of the debate may not be rooted in the nature of the problem itself, but rather in the scientific, technical and societal framings used to present it.

The second major conclusion of this work is therefore that it should be possible to reconcile the agendas of the two sides of the meat story. In fact, there is no technical impossibility to *simultaneously* reduce the consumption (and production) of red meat directed at consumers in high and middle-income countries, while at the same time boosting protein consumption among the socio-demographic groups and populations for which more protein in their diet would be beneficial. The polarized nature of the debate between the livestock proponents and the alternative protein proponents is therefore the result of a strawman argument that prevent the system from transitioning toward more sustainability, and benefits only those who have strong financial, economic, or professional interests in maintaining the system in its current lock-in. It is up to the rest of us to make this change happening.

Data availability statement

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Author contributions

CB contributed to conception and design of the study and wrote the first draft of the manuscript. CB and ML wrote all sections of the manuscript and contributed to manuscript revision, reading, and approval of the submitted version. All authors contributed to the article and approved the submitted version.

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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.

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Quitting livestock farming: transfarmation pathways and factors of change from post-livestock farmers' accounts

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Transitioning away from livestock farming would limit the carbon footprint of humanity and reduce the pressure on water, land and biodiversity. It would also improve human health, as animal farming increases the risks of pandemics and bacterial resistance. All of these risks and opportunities make a compelling case for a transition towards plant-based diets. In case of a large-scale transition, hundreds of thousands of farmers would have to quit animal farming and switch to other activities. Such transition is potentially happening in developed countries, where industrial operations are located, consumption *per capita* is the highest and alternatives to animal products are increasingly available. However, there is considerable resistance from farmers to this transition. There is thus a need to better understand potential transition pathways to support smooth transitions. To do so, 27 stories of farm transitioning out of livestock farming – so called *transfarmation* – were collected. Most of these cases are located in Switzerland and the US. These accounts were published on the websites of organizations that support farmers transitioning out of livestock production or by farmers themselves. In this qualitative study, I coded these accounts to identify patterns in the drivers, behaviour, and decision-making of farmers explaining their transition. Two main patterns were identified: (1) transfarmations from intensive poultry or pig farms towards a mushroom or market gardening farm, driven by economic interests and (2) transfarmations driven by compassion to animals, mostly leading to a farmed animal sanctuary or market gardening farm. Support organizations for transfarmation seem to be particularly beneficial for the second type of transition. I conclude this paper with research perspectives on the topic of transfarmation, especially on the role of gender and the potential of transfarmation for the green care economy.

KEYWORDS

transfarmation, livestock farming, compassionate, post-livestock transition, farmed animal sanctuaries, green care, care farm

1. Introduction

There is a growing body of evidence that livestock farming is detrimental to health, the environment and the climate. Meta-analysis has shown that whatever the type of livestock, the farming of animals decreases the abundance and diversity of species, especially in relation to wild herbivores and pollinators (Filazzola et al., 2020). There is now clear evidence that animal products have a major impact on several dimensions of our ecosystem's health (Leip et al., 2015;

Godfray et al., 2018; Springmann et al., 2018; Willett et al., 2019). Animal products have the largest effect on the carbon footprint of diets (Poore and Nemecek, 2018; Sandström et al., 2018), especially in countries with high Human Development Index scores (Romanello et al., 2022). Reducing ecologically harmful production could make our food system emission-neutral by the end of this century (Bodirsky et al., 2022) as well as making land available for natural vegetation and its associated biodiversity (Sun et al., 2022). Finally, quitting livestock farming would free around two and a half billion hectares of land (Mottet et al., 2017), thus potentially freeing space for biodiversity.

In addition to the environmental effects of livestock farming, a high consumption of animal products has detrimental health effects on human consumers. Increased red meat consumption is correlated with an increased risk of stroke, diabetes (Larsson and Orsini, 2014) and cancers (Chan et al., 2011; Bouvard et al., 2015; Farvid et al., 2021). In contrast, a higher consumption of fruits and vegetables is associated with a longer life expectancy (Bellavia et al., 2013) and a whole food, plant-based diet reduces the risks associated with obesity, heart disease and diabetes (Wright et al., 2017). Furthermore, livestock farming consumes 3 to 5 times more antibiotics than humans do worldwide, increasing the risks associated with antibiotic resistance (Landers et al., 2012). Finally, as livestock farming is a major driver of deforestation (Hecht, 1993) which in turn increases the diffusion of pathogens (Faust et al., 2018), livestock farming plays a role in triggering pandemics from zoonosis causing millions of human deaths every year and costing billions of dollars (Karesh et al., 2012). A rapid shift to more plant-based diets would save 11.5 million lives worldwide and limit the risk of zoonotic diseases (Romanello et al., 2022).

Based on these converging bodies of evidence, well-recognized scientific institutions focusing on health, biodiversity, and climate recommend reducing the consumption of animal product (IPBES, 2019; Shukla et al., 2019; WHO, 2019). The EAT-lancet commission proposed a balanced diet with significantly less animal products than current average diets in developed countries (Springmann et al., 2018; Willett et al., 2019). Dietary guidelines echo these trends as they advise to limit meat consumption compared to the current consumption levels of a typical western diet (Cocking et al., 2020). On the market supply side, recent years have seen a development of meat substitutes and alternatives (Malav et al., 2015; Lee et al., 2020) and plant-based meat alternatives have seen a significant growth in sales (Zhao et al., 2022). The future could also include a sustainable supply of cultivated meat (Kumar et al., 2021).

Based on similar recognition of the ethical, environmental and health impacts of livestock farming, recent years have seen the emergence of veganic agriculture. Veganic agriculture, or sometimes called stockfree farming (Schmutz and Foresi, 2017), aims at producing crops without the use of livestock and their by-products (typically manure). While veganism is usually considered as a consumption behaviour, veganic agriculture is an approach to agricultural production inspired by similar principles (Hirth, 2021). The recent emergence of this type of agriculture shows a trend towards disconnecting food production for humans from the use of livestock on farms.

While a decline in meat consumption and rise of meat alternatives would mean tremendous benefits for health and the environment, it might also mean a significant social cost to livestock farms. For example, the Dutch government announced recently a 30% reduction in livestock in order to comply with EU standards on nitrogen pollution. The Netherlands, a leading food producing country, had the most intensive livestock density in Europe with 3.8 livestock units per hectare in 2016 (the EU average is 0.8) (EUROSTAT 2016), leading to a nitrogen crisis (Erisman, 2021). The government announcement triggered protests from livestock farmers in the country because it jeopardizes the survival of many farms. This event shows that if meat consumption were to be reduced significantly in the future, strong resistance from livestock farmers could be expected. Such resistance could potentially be reduced by supporting farmers in smooth transitions out of livestock farming, but little is known about such transitions.

Transitions out of livestock operations have mostly been considered from an economic perspective (Son et al., 2022), where smaller and less productive operations are pushed out by competition, the so-called "agricultural treadmill" (Ward, 1993; Levins and Cochrane, 1996). In this perspective, farming operations are considered as regular firms, looking for the best economic opportunities. However, in the Netherlands, a strong economic support of 25 billion Euros for transition did not seem to satisfy livestock farmers, and public authorities are therefore looking for alternative ideas to support transitions. In particular, little is known about the main motivations for some farmers to transition out of livestock farming. Which new activities would be open for them once they would take that decision? What support can be provided by organizations supporting transfarmation? This article aims to shed light on such processes by studying cases of voluntary transitions out of livestock farming – so called "transfarmation." By "voluntary" transition, I mean a transition where farmers are not directly coerced to quit livestock farming. Current post-livestock farms or "transfarms" are limited in numbers but can provide valuable lessons that could help authorities and farmer-support organizations identify farms best suited for transitions and channel funding to key support services. To learn from the "transfarm" examples, I collected stories of transfarmations published online by organizations that support transfarmation or by farmers themselves. Using qualitative analysis, I coded these stories of farm transition pathways in order to identify (1) the main motivations to transfarm, (2) the type of farm these farmers transition to, and (3) the type of support transfarmation organizations provide. Finally, I discuss the future of transfarmation for different farm trajectories identified as well as future research perspectives on the role of gender, and on the complementarity of transfarmation with demand-side policies to reduce meat consumption. The last section of the discussion introduces some key limitations of this study.

2. Methods

I collected stories of 27 farms (see Table 1) that voluntarily decided to quit livestock farming. Through an internet search and contact with the French organization TransiTerra, I identified websites of organizations that support these transitions: Refarm'd (UK), TransFARMation (CH), Rancher Advocacy Program (United States), The Transfarmation Project (USA), Farm Transformers (USA), Stockfree Farming (UK), Hof Narr Association (CH) and It's cowtime (DE). Although a comprehensive search was conducted in French, English, and German, some farms may have been missed, especially in other languages. I identified 27 farms on these organizations' websites. Most of the cases come from the Unites States of America (13) and Switzerland (10). Although a specific search was conducted, no case of transfarmation

TABLE 1 Dataset of transfarms with the source of stories.

ID	Name of farm	Country	Source
1	Biohof Hübli Tierarche seeland	Switzerland	https://www.biohof-hübeli.ch/über-uns/team/
2	Bradley Nook Farm	UK	https://sites.google.com/d/1nR334gorwP8KzlvBA_OA6_Sr15HLDuzR/p/1oSKaMw2lgfInEwKVXxJUuPdW2lL7U13v/edit
3	Lebenshof Aurelio	Switzerland	https://www.lebenshof-aurelio.ch
4	Lebenshof KuhErde	Switzerland	https://www.kuherde.ch/lebenshof/
5	Lebenshof Frei sein	Switzerland	https://www.lebenshof-freisein.ch/lebenshof
6	Lebenshof "Einfach Sein"	Switzerland	https://piabuob.ch
7	The Barrett family	USA	https://rancheradvocacy.org/the-barrett-family/
8	Rowdy girl sanctuary	USA	https://rancheradvocacy.org/rowdy-girl-sanctuary/
9	The Traylors	USA	https://rancheradvocacy.org/the-traylors/
10	Halley farm	USA	https://thetransfarmationproject.org/our-farmers/halley-farms-successful-chicken-to-hemp-transfarmation/
11	Carolina mushroom farms	USA	https://rancheradvocacy.org/carolina-mushroom-farms/
12	Farmhouse garden animal home	USA	https://www.farmhousegardenanimalhome.com
13	Mike weaver	USA	https://rancheradvocacy.org/mike-weaver/
14	Starlove Ranch	USA	https://farmtransformers.org/starlove-ranch-usa/
15	Craig Watts	USA	https://thetransfarmationproject.org/our-farmers/craig-watts-is-transfarming-his-former-poultry-farm/
16	Vegangården	Sweden	https://farmtransformers.org/vegangarden-sweden/
17	Broken Shovels	USA	https://farmtransformers.org/broken-shovels-usa/
18	The sanctuary at Soledad Goats	USA	https://sanctuaryatsoledad.org
19	Hof Naar	Switzerland	https://www.hof-narr.ch
20	Northwood Farm	UK	https://stockfreefarming.org/from-beef-and-dairy-to-veganic-cereals/
21	Naturhof Waltwil4	Switzerland	https://www.naturhof-waltwil-4.ch
22	Hofgut Rosenberg	Switzerland	https://hofgut-rosenberg.ch
23	Lebenshof Bruffhof	Switzerland	https://www.bruffhof.com
24	Hof-Lebensparadies	Switzerland	https://hof-lebensparadies.ch
25	Hof Butenland	Germany	https://www.stiftung-fuer-tierschutz.de
26	Tom & Sokchea Lim	USA	https://thetransfarmationproject.org/our-farmers/tom-and-sokchea-lim-are-building-their-dream-vegetable-and-mushroom-farm/
27	JB farm	USA	https://thetransfarmationproject.org/other-farmers/paula-and-dale-boles-transitioned-their-poultry-farm-into-greenhouses-for-microgreens-hemp-flowers-and-specialty-vegetables/

was found in France. I then looked for stories written directly by farmers themselves. To do so, I searched for the website of each farm and collected their story if available. When a story directly written by the farmers was not available, I used the story written by the support organization. In two instances, two support organizations had a different story for the same farm. In these two cases, I grouped both stories together as a single story. With this method, I collected 16 stories directly written from farmers, and 11 from support organizations. For stories originally published in German, I used the DeepL translator to translate the stories into English, which is a fast, efficient and economical option for translation. The length of these stories varies from 219 words for the shortest to 2,497 words for the longest. The average length is 770 words.

I performed a qualitative analysis of the text of transfarmation stories in order to shed light on the different steps experienced and decisions made by farmers from a livestock farm to a post-livestock farm, as well as the factors that enabled this transition. The analysis was performed using the software MAXQDA (Version 22.3.0), a recognized tool for qualitative analysis. First, I explored an approach of top-down coding using classical theories of change, namely the transtheoretical model (Prochaska and DiClemente, 2005) and the theory of planned behaviour (Ajzen, 1991). However, this type of coding was unable to capture the depths of stories, probably because these theoretical frameworks are specialized towards individual change in the context of unhealthy behaviour, typically addictions such as smoking or alcohol. Consequently, the data coming from this first coding attempt is not used in the analysis included in this article. Therefore, I performed a bottom-up approach with codes emerging from the texts themselves. This approach resulted in 15 main codes and sub-codes. A set of variables about each farm was also collected from the stories: the type of farm before transfarmation, the type of farm after transfarmation, the future of animals after transfarmation, gender of the transfarmer (woman, man, or both woman and man), motivation for transfarmation (see Table 2). After bottom-up coding, I analyzed the content of the codes that occurred most frequently in the stories, focusing on codes with more

TABLE 2 Transfarms and the coding of main variables.

Id	Farm	Country	Type of farm before	Type of farm after	Future of animals	Gender of transfarmer	Motivation
1	Biohof Hübli Tierarche seeland (CH)	Switzerland	Dairy cows	Market gardener	Sponsorship	Male	Political
2	Bradley Nook farm (UK)	UK	Dairy cows	Market gardener	Partial transfer to sanctuary	Male	Compassion, environmemt
3	Lebenshof Aurelio (CH)	Switzerland	Dairy cows	Oat drink	Sponsorship	Male & Female	Compassion
4	Lebenshof KuhErde (CH)	Switzerland	Suckler cows	Sanctuary	Sponsorship & donation	Female	Compassion
5	Lebenshof Frei sein (CH)	Switzerland	Suckler cows	Carefarming	Sponsorship	Male & Female	Compassion
6	Lebenshof Einfach Sein (CH)	Switzerland	Bovine	Market gardener	Sponsorship	Female	Compassion
7	The Barrett family (USA)	USA	Chicken	Mushroom	End of contract	Female	Compassion, health
8	Rowdy girl sanctuary (USA)	USA	Cattle	Sanctuary	Sponsorship & donation	Female	Compassion
9	The Traylors (USA)	USA	Cattle	Crops	Transfer to sanctuary	Female	Compassion
10	Halley farm (USA)	USA	Chicken	Hemp	End of contract	Male	Economical, health
11	Carolina mushroom farm (USA)	USA	Pig	Mushroom	Unknown	Male	Economical
12	Farmhouse Garden Animal Home (USA)	USA	Cattle	Market gardener	Sanctuary	Male	Compassion
13	Mike Weaver (USA)	USA	Chicken	Hemp	Unknown	Male	Economical
14	Starlove Ranch (USA)	USA	Cattle	Market garden & event organizer	Sanctuary	Male & Female	Environment
15	Craig Watts (USA)	USA	Chicken	Mushroom	Unknown	Male	Economical
16	Vegangården (SW)	Sweden	Pig	Market garden & event organizer	Unknown	Male & Female	Compassion
17	Broken Shovels (USA)	USA	Dairy goat	Sanctuary	Sponsorship & donation	Female	Compassion, environmemt
18	Sanctuary at Soledad Goats (USA)	USA	Dairy goat	Sanctuary	Donation	Male & Female	Compassion
19	Hof Naar (CH)	Switzerland	Unknown	Market gardener and sanctuary	Sponsorship & donation	Male & Female	Compassion, environmemt
20	Northwood farm (UK)	UK	Dairy cows	Crops	Unknown	Male	Compassion, environmemt
21	Hofnatur Waltwil4 (CH)	Switzerland	Cattle	Market garden & event organizer	Sponsorship	Male & Female	Compassion, environmemt
22	Hofgut Rosenberg (CH)	Switzerland	Suckler cows	Sanctuary	Sponsorship	Female	Compassion
23	Lebenshof Bruffhof (CH)	Switzerland	Cattle	Unknown	Partial transfer to sanctuary	Female	Compassion
24	Hof-Lebensparadies (CH)	Switzerland	Dairy cows	Sanctuary	Sponsorship & donation	Male	Compassion, environmemt
25	Hof Butenland (DE)	Germany	Dairy cows	Sanctuary	Transfer, sponsorhip and donation	Male & Female	Compassion
26	Tom and Sokchea Lim (USA)	USA	Chicken	Market garden	End of contract	Male	Economical
27	JB Farm	USA	Chicken	Market garden & Hemp	End of contract	Male & Female	Economical

than 15 text segments. Thus, the analysis focused on 6 main codes: "Empathy to animals" (162 segments), "External support to transition" (90), "Environment" (41), "Financial issues" (20), "Vegetarianism and veganism" (36), "Organic" (16). For each main code, I read all segments of this code and wrote a synthesis of the content in an associated memo (as per the MAXQDA terminology). The memo is usually in the form of text. For the code "external support to transition," I produced a figure to synthesize the support process. Each memo also extracted some key citations for illustration of a specific aspect. These citations are also used in the result section of this article. When a code included some sub-codes (for "Empathy to animals" and "External support to transition" codes), the memo detailed specific aspects of each sub-code.

3. Results

In the result section, I detail the main elements that explain transfarmation based on the farm stories. The first three sections detail the three main motivations to transfarm: compassion, economic and environmental. Among 27 farms studied, 19 mention compassion as a main motivation for change. The two other main motivations of transfarmation are the environment (7) and economics (6). For six of these farms, the motivation is both compassion and the environment. For the twelve farms motivated by compassion, the decision to transfarm was taken only by a woman on 6 farms. The decision was taken by a woman and man together on 5 farms. When transfarmation is motivated by the economy, it is a decision taken only by a man in five of the six stories (Table 2). The fourth section describes the range of transfarmation from one farm model to another. The last section introduces the key role of external support in the transfarmation process. I use quotes from the collected texts to illustrate the results. The identification number of each farm is given in brackets, in line with the identification number in Table 1.

3.1. Most transfarmations are motivated by compassion

A majority of the studied farms share a sense of compassion for the non-human animals previously raised as livestock. The expression

of compassion for animals includes four different non-exclusive elements. I introduce these four elements below together with one quote and then detail some aspects of them in a meta-narrative paragraph about the sense of compassion for non-human animals.

(1) **Sensitivity to suffering** in relation with the slaughtering of raised animals and the separation at birth of the mother cow and her calf. E.g: "*The sorrow I felt for their condition, the pain I felt when they all were sent to slaughter was no longer something I could transcend.*" [7].
(2) **Love for animals** and desire to care for them. E.g: "*I fell in love with all the critters….kinda like Elly Mae Clampett – I named them all and loved them everyone – I'd go out and spend time with them, dance around them – sing to them and talk to them.*" [8].
(3) **Recognition of animal rights** (and lack thereof) by giving a voice to the voiceless, recognizing animal individuality and creating a society based on principles of co-existence. E.g: "*That is why we decided to move forward step by step into a new future by founding animal sponsorships, where every living creature is allowed to exercise its right to a happy, healthy and long life.*" [23].
(4) **Acknowledgment of injustice** in relation to the killing of animals that are no longer economically performant. E.g: "*I do not think it's right that the hybrid chickens are bred for performance in such a way that they have to be replaced because of their declining performance*" [21].

Sending animals to the slaughterhouse is the act that most often triggers transfarmation, as farmers feel negative emotions, mostly pain, sorrow and sadness when doing so. This happens especially when animals are put in the transport to the slaughterhouse or in the sale barn. These two places seem to symbolize the irreversibility of the decision. These negative emotions are consistent with the care and love felt by compassionate farmers to their animals. Emotions of care and sadness about the death and loss of an animal are at odds with being responsible for sending the animal to slaughter – a classic case of cognitive dissonance (Festinger, 1962). Raised animals are sometimes named "*faithful companions*" [4] or "*wonderful fellow creatures*" [24]. These farmers recognize the individuality of animals and call them by their name. In particular, cows are praised for their care for calves ("*Honey was a tame, gentle cow who loved all the babies*" [9]) and their suffering when separated from them is acknowledged ("*the experience of watching them leave, the mamas wailing for a week and the absence of their souls in the pasture haunted me*" [8]). One farmer expresses directly that the repression of these emotions is important and taught at an early age: "*I thought I was giving my children some sort of gift by toughening them up or desensitizing them to the reality of farming at an early age. I was in high school when we raised our first batch of chickens and I was traumatized the first time I saw them all being caught and hauled away in trucks, knowing their fate. I really believed that it was beneficial to educate my children from an early age to know the reality of food production. The chickens, cows, pigs, and goats were a commodity. Any sentimentality was accepted as a cute novelty, but we all knew not to get too attached or to show too much emotion.*" [7]. These emotions are never totally repressed for these farmers ("*It hurts me every time (…) this removal was always difficult to me*" [21]) and the difficulty of dealing with these emotions accumulates over time ("*more and more unbearable to me*" [22]; "*becoming more and more overwhelming*" [5]) until it seems to reach a threshold where it is no longer bearable ("*She would rescue goats that she could not bear seeing go to slaughter*" [17]; "*I could not stand to watch the babies leave their mamas even one more time to go to the sale barn FOR SLAUGHTER.*" [8]). Passing this threshold triggers the necessity to act ("*I had to do something to prevent that from ever happening again*" [8]; "*From now on, I will not send any more animals to their death*" [24]). Once the decision is taken, the first priority is to stop the slaughter; finding a solution to sustain the farm without the income of selling animals usually comes second. While the confrontation with one's emotions is usually personal, the second step triggers the need for external support (see Section 3.5).

3.2. Transfarmation motivated by financial troubles

Economic difficulties can be a strong incentive to transition out of livestock farming. All transfarms with this type of motivation are from the United States. Among these 6 farms, all of them used to have intensive operations with animals living in high density. Five of these farms raised chickens and one raised pigs. Chicken farmers operated in the system of "contract farming," raising hundreds of thousands of chickens per year. The chicken industry in the US is depicted as particularly hard for farmers that are "*isolated from other farmers and had no say on how the chickens were raised*" [27], "*living in constant fear that they* [the company they contracted with] *would let us go and we could not pay the bills*" [26]. This system seems to trigger health issues among them: "*When faced with mounting financial and health troubles from chicken farming, Bo and Sam decided to give up raising birds for good*" [10]. Farmers in this system usually go into debt to build facilities where they will raise the animals delivered to them by the contracting company. Maintaining viable profits on such contracts seems particularly difficult. One farmer mentions that "*they were losing five dollars on every pig leaving their farm*" [11], and another that "*the income from chicken farming proved to be unreliable*" [10] thus "*paying off their debt extremely difficult*" [10]. Even when they manage to pay off their debts, one farmer mentions the "*debt treadmill of poultry farming*" that forces them to incur new debts "*creating a vicious cycle of debt that leads to financial insecurity and bankruptcy*" [10]. Mike Weaver, one of the transfarmers, became a spokesperson denouncing this system in the US. Transfarmers that quit this type of contract farming face the difficulty of postponing debt payment without an income. However, their transition is facilitated by the fact that they do not own the animals and can "simply" end the contract. In other words, they are not responsible for the future of the last animals they raised. They can also capitalize on the buildings they invested in to reinvent their farm.

3.3. Transfarmation motivated by the environment

The environment is the primary trigger of the transfarmation in only one case: "*Humanity's dependence on fossil fuels or animals is not sustainable. We have to change with the times and focus on renewable resources. There's a shift away from systems powered by consumption and we are moving into building value instead*" [14]. Environmental

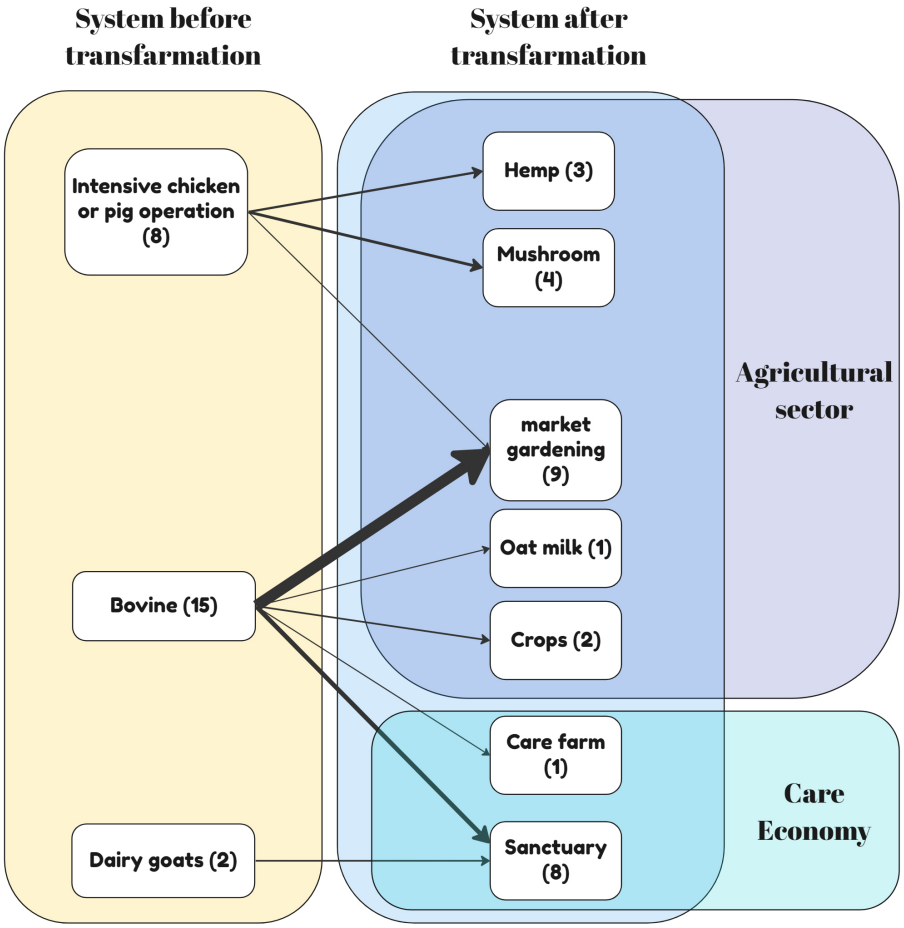

FIGURE 1
Farming system before and after transfarmation. Arrow size is proportional to the number of farms that transitioned along this pathway.

consideration is usually a secondary source of motivation. In the case of the Traylors for example, the husband consented to transfarm based on environmental arguments but this came after the original decision to transfarm was taken by his wife on compassionate grounds: "*Richard had an epiphany. He recognized that being an environmentalist, he was a hypocrite if he took the cows to market!*" [9]. Within the small number of farmers studied here, environmental consciousness seems to act mostly as a catalyser of transfarmation rather than a root cause.

Three farmers [2, 20, 25] mention that a transition to organic farming preceded their transfarmation. While organic standards allow for better welfare for the animal "*reducing the size of the herd, enlarging the barn, abolishing tethering*" [25], organic standards do not solve the emotional tension mentioned in section 3.1, "*But even "organic" is not an ideal world: if a cow's milk yield declined, she was no longer pregnant or sick, she was slaughtered.*" [25]. For these organic farmers with compassionate motivation, the transition to organic is only a transitory step towards transfarmation.

3.4. Transfarmation pathways and models

In this section, I introduce an overview of the different pathways taken by the different farms studied here (Figure 1). The following paragraph provide some details about the most popular evolutions.

Coming from more extensive goat or bovine systems of production, the main system chosen for transfarms is the sanctuary model, where the farm dedicates itself to sustaining the lives of the animals living there and eventually sheltering new animals. This is consistent with the fact that 15 out of these 17 farms are motivated to transfarm by compassion (see Table 2). In the sanctuary model, the living costs of animals are usually met by sponsorships and donations. In this model the farm leaves the productive agricultural sector to enter the "care economy." While the term "care economy" usually applies to humans, and usually mostly women, taking care of other humans (Folbre, 2006), I believe it can also be adapted to these farmers who dedicate their life to the care of non-human animals. Some systems called "care farms" (Hassink and Van Dijk, 2006) combine care for humans and care for non-human animals, as this system involves using the sheltered animals for therapeutic purposes. The other most popular transition for extensive bovine systems involves remaining in agriculture and producing fruits and vegetables on small holdings. Such market gardening relies on the small-scale production of labor-intensive and high added-value horticultural products.

For intensive systems raising pigs and chickens, all from the US, the most popular alternatives are to produce mushrooms or hemp, and market gardening. Mushrooms and market gardening have the advantage that buildings formerly used to raise chickens can be reused as mushroom fruiting chambers or as greenhouses. These farms are

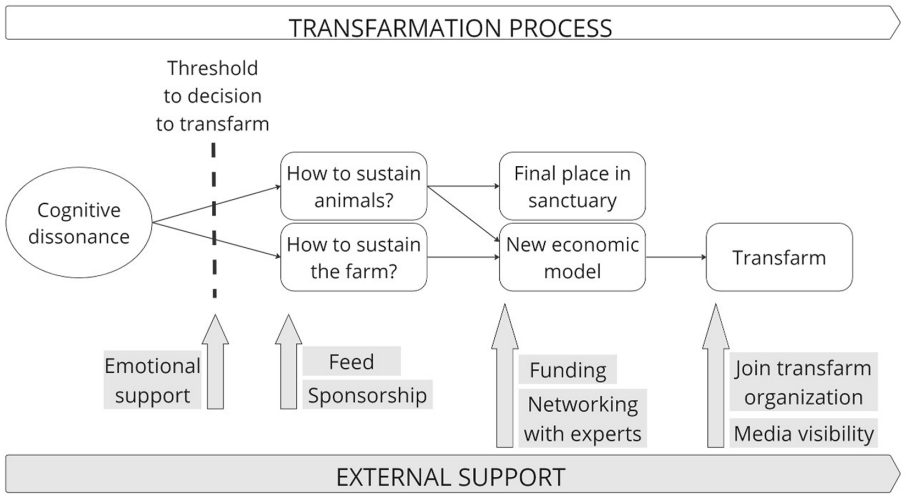

FIGURE 2
Model of transfarmation for a compassionate farm with the elements of external support that can facilitate the process. Cognitive dissonance, as defined by Festinger (1962), refers to the feeling of discomfort of an individual holding two contradicting beliefs or attitudes. Typically in the case of transfarmation motivated by compassion, the contradiction between the belief to care for animals and the action to kill them.

mostly economically driven in their desire to transition their farms to other agricultural systems of production, as the compassionate motivation is only present in 2 out of the 8 intensive farms and none of them turned into sanctuaries.

3.5. External support in the transfarmation process

The role of external support is central to the transition process. Support is particularly critical for transfarmation with compassionate motivation. As described in Section 3.1, these are times of uncertainties and emotional distress for some: "*One very cold and dark day, I sat down with all my brokenness, confusion, and desperation and wrote a letter to the universe asking for help. There was an intrinsic knowing that we would never be able to dig out of this alone. And, it turns out, there were people out there willing to help us out of our situation*" [7]. Once the decision to stop selling animals is taken, transfarmers encounter two main problems: (1) finding food and shelter for the animal on the short term and (2) finding a production system to sustain the farm in the mid-term. The Figure 2 below synthesizes the process of transfarmation with the role of external support.

In all the stories collected for this article, two organizations, Rancher Advocacy Program (RAP) and Hof Narr, stand out for their centrality in supporting other transfarmations as they have, respectively, 10 and 9 farms being affiliated (see Figure 3). I considered a farm to be affiliated to a support organization when its name was referenced in the support organization website. As a consequence, the same farm can be affiliated to several organizations. RAP and Hof Narr were created by two women and transfarmers [8] and [19] and they are mentioned in stories as key agents of change. From famers' stories, this support from RAP and Hof Narr is provided through:

(1) helping to find a place for animals through their network "*That is how we came across the Narr farm, among others. With their existing network and their experience in building a life farm, they supported us in realizing our vision*" [24]. Sometimes by directly taking some animals in their sanctuary or taking over the sponsorship of some animal: "*When Sarah told me that the association Hof Narr would take over the sponsorship for this cow, it was Christmas, Easter and everything together for me.*"[4].
(2) providing information and support for short-term economic sustainability "*she was at my farm the very next day organizing and executing a fund raiser to get us hay. The next 24 h were a whirlwind of generosity and we met our fundraising goal, bought hay, and had money left over to buy diesel. The logistics of how this all played out still baffles me.* "[7] or more long-term solutions: "*they are helping us by providing links to possible grants and loans*" [9].
(3) giving information and advice about the transition, sometimes mobilizing experts: "*Renee set up zoom meetings with the "best of the best' in agriculture and ranching. Individuals who gave us many ideas on what would suit us.*" [9].
(4) providing emotional support: "*Without Renee and Tommy's encouragement and support, we would not have even thought about this endeavor.*" [9].

As a final note, other forms of support appear to play a more modest role in transfarmations documented here. Two farms [8, 16] mention the role of the "vegan community" as a support for buying products from transfarms or making successful crowdfunding campaigns. The Transfarmation Project, Farm Transformers, Refarm'd, Stockfree Farming and It's cowtime support organizations seem to play only a minor role in the stories of transfarmations.

4. Discussion

4.1. The futures of transfarmations

Transfarmation is still a niche innovation where innovators are organized in small networks of individuals driven by their vision

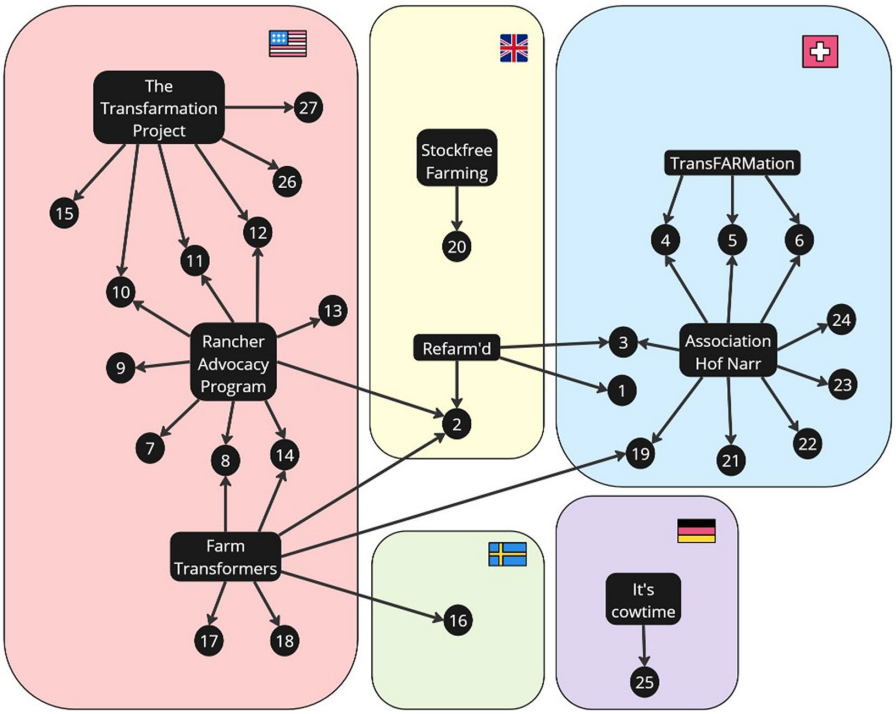

FIGURE 3
Networks of farms and their affiliations to transformation support organizations (in black rectangles) in different countries. Farms are numbered from 1 to 27 according to Table 1.

(Geels and Schot, 2007). Among these small networks (Figure 3) I identified two main types of vision about the future of transformation depending on the main motivation: based on either economics or compassion towards animals. This section discusses the potential evolution of some of the pathways identified and their potential for scaling up and tackling the health and environmental challenges of livestock operations.

Economically driven transformations come from intensive livestock operations that encounter economic difficulties, mainly among intensive operations raising pigs or chickens. Such transformations have the highest potential for ethical and environmental impact due to the scale of their production. The study here shows some farm transitions that involved leaving livestock farming, such as transitions from poultry operations to mushrooms or market gardening. However, if the motivation would be purely economic, the transformation process may be reversible if new economic activities involving raising animals become economically interesting. Also, it seems that this type of transformation is triggered by exploitative working conditions that are quite specific to the United States.

Half of the farms motivated by compassion transitioned to another agriculture production system. The most common system is market gardening (5 out of 9 farms that remained in the agricultural sector). A third of the 19 farms motivated by compassion transitioned to a farmed animal sanctuary model. Some authors refer to this model as the "refuge + advocacy" model, as they not only shelter animals but also have an educational role (Donaldson and Kymlicka, 2015). While ensuring a much better life for the animals rescued, this model comes with new difficulties. The sanctuary model still relies on animals living in captivity as well as actively restricting their natural behaviour, such as reproduction (Abrell, 2019). The main role of farmed animal sanctuaries is not to be an alternative to livestock farming but to educate the public to animal welfare with rescued animals as ambassadors (Abrell, 2019). Given the number of livestock in the world (Bar-On et al., 2018), sanctuaries can only play a niche role. To go beyond this model, the authors of Zoopolis (Donaldson and Kymlicka, 2011) suggest that sanctuaries should consider rescued animals not just as representatives of other animals who did not escape livestock farming (or "ambassadors") but as individuals having a say in matters that concern them (or "citizens") in inter-species communities (Donaldson and Kymlicka, 2015). Thus, sanctuaries could become incubators of new social arrangements between humans and non-human animals. These small-scale innovations could be blueprints for wider diffusion to society as a whole.

Among farms motivated by compassion, the Lebenshof Frei Sein, despite being a single case, is an interesting model for transformation related to the care economy. More broadly, this type of activity is part of the green care economy, where "nature" is used for health purposes (Haubenhofer et al., 2010). Care farming specifically involves domesticated animals in therapeutic interventions. Positive effects of these interventions on patients have been measured (Elings, 2012; Leck et al., 2015). The therapeutic benefits of care farms are rooted in human-animal interactions (Leck et al., 2014; Hassink et al., 2017). Care farms tend to consider non-human animals as co-workers, thus going further than the sanctuary model by not only recognizing previously farmed animals as victims but as agents who actively participate in an inter-species community. Considering non-human animals as workers raises the question of the "humane job" (Coulter, 2017), where non-human

animals in the green care economy should not find themselves in new forms of degrading or lethal work. For Cochrane (2019), providing "good work" to a domesticated animal is possible under the condition that they take pleasure in the activity, can use and improve their skills, and that their agency is recognized in a community that values their contribution. While the positive effects of such farms on humans are more and more documented, establishing the conditions of a "humane job" for animals in care farms is still an understudied topic. Nevertheless, this re-orientation of productive farms to care farms offers interesting perspectives as a source of income and good reputation for farmers and for the agricultural sector as a whole (García-Llorente et al., 2018). However, it also requires specific skills from farmers to deliver these interventions and might require significant investment in training and education. Finally, it is also quite uncertain how many of such care farms would be actually needed before saturation of therapy needs.

Finally, our results show the key role that support organizations can provide to help transfarmers, especially those founded by transfarmers themselves. There is evidence that farmer-to-farmer support is particularly efficient to help transitions. The key role of such organizations has been extensively researched in the context of transition from conventional to organic agriculture. For instance, in Switzerland, the lack of a peer network to support transitioning organic farmers has been shown as a major impediment to change (Home et al., 2019). Studies from Ireland and Mexico indicate that knowing another farmer who transitioned to organic farming has a positive impact on the decision of a farmer to adopt organic farming (Hattam et al., 2012). Such support organizations could expand their support services in the future to help transfarmers to market their product. For instance, while the post-livestock farmers in our sample appear to show only limited interest in veganic agriculture (as only two farmers actually mention this approach in their farming practices) a study conducted in Germany showed that 17% of its respondent consumers are interested in products produced by veganic agriculture (Jürkenbeck and Spiller, 2020). This suggests a virtually untapped consumer base. However, veganic agriculture still has many technical, agronomic and socio-economic challenges (Schmutz and Foresi, 2017; Mann, 2020; Seymour and Utter, 2021). In this regard, Hirth (2021) details the case of the Bradley Nook Farm, one of the farms in this case study. One agronomic difficulty is for organic farmers to cultivate crops without livestock and thus without animal manure. In that sense, organic agriculture may only feed a large human population with intensive use of green manure and legumes (Chatzimpiros and Harchaoui, 2023). Another challenge is to conserve or find a substitute for manure as a source of habitats for soil biodiversity (Köninger et al., 2021). Even so, the veganic farming movement shows promise to radically transform and address some of our current food systems shortcomings (Nobari, 2021).

4.2. Research perspectives

A first direction for research is about the role of gender in transfarmations. We have seen that, when it comes to support transfarmations, the two most active and central individuals are women. We also saw that the decision to transfarm is shared in equal numbers between genders. The results hint towards an equal share between genders in decisions to transfarm, suggesting a difference with traditional decision making about production in farms where men have the lead (Pandey et al., 2011). When compassion is the main motivation, women seems to play a key role. This tendency corresponds to women being on average more empathetic than men (Christov-Moore et al., 2014) and women having more empathy to non-human animals (Taylor and Signal, 2005). Knowing more about these gender specificities could help transfarmation support organizations to target their communication and tailor their actions.

A second direction for research is about the best way to steer farms out of livestock farming while avoiding conflict as much as possible. Transfarmation is potentially a supply-side solution for decreasing livestock by limiting the offer of animal products from farm owners to the market. However, it is still very uncertain how transfarmations could be scaled up to have a meaningful impact on the supply side. Therefore, complementary solutions on the demand side also need to be considered. Some policies may involve higher prices of animal products with information and nudging (Kurz, 2018; Vellinga et al., 2022). For example, a meat tax was implemented in Denmark but was repealed by influential opponents shortly after despite positive health outcomes (Vallgårda et al., 2015). At the EU level, a multi-stakeholder participatory policy, designed to engage with these powerful opponents, could establish consumption corridors to limit the quantities of animal products available according to social, nutritional, ethical and environmental factors (Fuchs et al., 2016; Cué Rio et al., 2022). The consumption corridor concept aims at establishing minimum and maximum standards for consumption to guarantee a good quality of life for everyone (Di Giulio and Fuchs, 2014). The balance of all these tools (support of transfarmation, tax, nudges and consumption corridors) for a post-livestock economy remains to be investigated.

4.3. Limitations of the study

The main limitation of this study is its data collection method. As this is desk research, I did not collected directly all stories, but were written by either the support organization or the farmers themselves. Therefore, the context in which these stories were written was not under my control, which could create bias. For instance, when farmers publish their story on the website of their farm they might want to portray themselves in a positive light to attract customers to buy their products, motivate readers to sponsor an animal or donate to their sanctuary. Similarly, support organization might have an interest in appearing particularly helpful to motivate other famers to join their organization or to trigger donations. Additionally, elements mentioned in these stories are at the writer's discretion, which limits comparability between stories. Conducting interviews with farmers with the same set of questions could lead to more in-depth insights and greater comparability. In particular, more details about the economics of such transfarmation could be particularly helpful as most stories barely scratch the surface on such challenges. Furthermore, because I could not ask questions to farmers in this study, certain aspects may have been omitted from the stories. For example, some farmers do not explain the future of the last animals in their possession at the time of the transition to a post-livestock farm. Some farmers might omit the role of their partner in the decision to change the farm, which limits what could be learned about the role of gender in transfarmation. The final limitation of this study is that it solely focuses on the experiences of farmers who transitioned away from livestock production systems. In order to gain a more comprehensive understanding of the topic, it

would be valuable to also investigate the perspectives of farmers who were unable to make the transition or who are opposed to it. These alternative viewpoints could offer insights into the obstacles that hinder successful transformation.

5. Conclusion

In this article, I qualitatively analyzed the stories of 27 farms that decided to quit livestock farming. I identified two main processes based on their fundamental motivation, which was either economic or compassionate. We found that organizations that support the transfarmation process for compassionate purposes are critical to provide key services along the transition process. This support is probably legitimized by the fact that these organizations are founded by transfarmers. Economically driven transfarmations are often motivated by the desire to leave exploitative and health damaging working conditions. They mostly engage with transfarmation support organizations for new economic opportunities and technical support for new systems of production. The reuse of intensive farming buildings (poultry and pig) is particularly promising for mushroom or market gardening operations. Farms that want to keep interactions with domesticated animals have promising perspectives in the green care economy. Transfarmation is still a niche innovation that might become more relevant in the near future as some countries might reduce the number of livestock for economic, environmental, health or ethical reasons. Knowledge on the different motivations, pathways and necessary support can facilitate easier transitions.

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 contributed to all steps of the production of this article.

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Conflict of interest

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

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The land use, trade, and global food security impacts of an agroecological transition in the EU

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The need for an agroecological transition is regularly advocated by many actors and policymakers on the European scene, but many questions arise regarding the potential consequences that this transition may have on the rest of the world. Using a world biomass balance model, in this paper we show that a deep agroecological transition in the EU, if accompanied by a shift of EU food regimes towards more plant-based diets, is not detrimental to global food security. Without increasing its cropland areas, the EU can maintain the same level of exported calories as in a business-as-usual scenario while reducing its import needs. This result holds true also in an alternative scenario in which the other world regions adopt agroecological production methods and healthier diets. In contrast, an agricultural transition taking place in the EU without a change of EU food regimes, would drastically increase EU food dependence on global markets and contribute to the expansion of agricultural land in the rest of the world.

KEYWORDS

agroecology, agricultural transition, DIETS, modelling, organic agriculture, TYFA

1. Introduction

In the last years, several biophysical scenarios at the European or world scale designed sustainable transitions for the European and the world agriculture (Erb et al., 2016; Muller et al., 2017; Karlsson et al., 2018; Poux and Aubert, 2018; Willett et al., 2019; Mora et al., 2020; Billen et al., 2021). Among these scenarios, the one examined by Poux and Aubert, named TYFA, aims at reconciling a logic based on greenhouse gas (GHG) emission reduction with a logic of biodiversity conservation in the European agro-systems. This scenario models a deep agroecological transition in the European Union (EU) by 2050. It involves a phase-out of synthetic fertilisers, pesticides and antibiotics on the supply side, and a shift towards more plant-based food regimes with a reduction of food waste on the demand side. In a future context where world food demand is expected to rise sharply as a result of the joint effects of dietary transition and demographic growth in emerging and developing countries (FAO, 2018), the TYFA scenario attracted some criticisms because it did not consider international trade between the EU and the rest of the world nor the eventual transition of agri-food systems that non-EU countries could experience as well.

Scenarios promoting an agroecological transition, as the TYFA one, are often criticised pointing out the fact that the changes involved could undermine current EU agricultural production levels and lead to increased global food insecurity, with potential negative effects for importing countries (Zahrnt, 2011; Baquedano et al., 2022; Leroy et al., 2022). In the last years, following the announcement of the European Green Deal (European Commission, 2020),

several analyses evaluated the potential consequences of the Farm to Fork and Biodiversity Strategies, and more generally of a large-scale agricultural transition in the EU. Some studies focused on biophysical aspects and evaluated the impacts of inputs use reduction on EU agricultural output, and the role of plant breeding in offsetting the drop of production (Noleppa and Cartsburg, 2021). Others gave particular attention to impacts on trade, commodities' prices, and producers' income (Beckman et al., 2020; Barreiro-Hurle et al., 2021; Bremmer et al., 2021; Henning and Witzke, 2021). The common feature of these studies is that they only focused on supply-side measures.

The first objective of this paper is to show that a deep agroecological transition taking place in Europe would not deteriorate the European agricultural trade balance and lower the EU contribution to global food security if this agroecological transition involves a shift in food regimes and in food waste jointly with the change of agricultural production methods. As shown in Röös et al. (2022) and in Rieger et al. (2023), introducing a change in food regimes can help the EU agricultural production system to lower its environmental footprint and meet EU policy targets. In contrast, considering exclusively one side of the EU agroecological transition *de facto* narrows this transition to only its potential negative effects on the EU agricultural production and trade balance and on global food security. Indeed, in such a case, the potential compensatory effects that a shift in diets and a reduction in food waste would generate in terms of lowering EU domestic needs are not taken into account. The second objective of this paper is to test if this result remains valid regardless of the future pathway retained by food systems in the rest of the world. More specifically we show how the impacts of the agroecological transition in Europe change when food systems in the other regions of the world remain on business-as-usual trends or initiate an agroecological transition together with the EU. We add to the literature in several ways. Differently from previous exercises, in this paper we simultaneously consider the change in food regimes, the trade flows between the EU and the other world regions as well as the trajectories that the other countries could take in parallel to the EU food system transformations. We also focus our analysis on global food security, and we use caloric trade balances as main indicator to estimate the level of food dependence in each world region.

In the following sections, we assess the impacts of three variants of the TYFA scenario. The first one is the original version, which includes a change in production systems and in food regimes in the EU. The second one is a truncated version of TYFA in which the change in diets does not take place and the EU population continues to adopt high caloric diets rich in animal and ultra-processed (NOVA classification, Monteiro et al., 2019) food products. Since a shift of food demand is identified as a key social factor to foster changes in food supply, this truncated version of TYFA has less internal consistency than the first variant. It is nevertheless discussed as it allows a sensitivity analysis to show the importance of involving food demand in agroecological transition. The third variant associates TYFA with an alternative future scenario for food systems in the rest of the world. It allows to test how the results of the TYFA scenario may change when an agroecological transition, involving changing production methods and a shift towards healthier diets, also takes place in the rest of the world.

2. Methods

2.1. The GlobAgri-Agt model

The world biomass balance model GlobAgri-Agt (Mora et al., 2020) is used to carry out simulations of contrasting scenarios of future world food systems by 2050. Based on FAOSTAT Commodity Balances (FAOSTAT Statistics Database, 2016), GlobAgri-Agt integrates 38 agri-food products and encompass 13 world regions, one of them being the European Union. The model is calibrated to the 2007–2009 average year (called "2010") and has a 40-year simulation time horizon. As other biomass balance models, for each agri-food product and each region, GlobAgri-Agt includes a resource-utilisation balance equation where domestic resources (production plus imports minus exports) equal domestic uses (food consumption, feed, seed and other uses, loss and waste, and stock change). Imports and exports are determined, respectively, as a fixed share of total domestic use and as a fixed share of the world market. A world equilibrium equation ensures that for each product the sum of world imports equals the sum of world exports. Finally, a constraint on maximum cultivable land for each region limits the potential expansion of cropland areas. In GlobAgri-Agt, population, diets, as well as some parameters such as crop yields, cropping intensities and animal efficiencies are fixed by the modeller as part of the simulated scenario, while production, land-use change, and trade are the outcomes of the model. Following changes in the use of agri-food products in one or several regions, GlobAgri-Agt works to balance resources and measures the impact of these changes in terms of production, land use and trade for every world region. The model works without a price adjustment mechanism. If one region exceeds its maximum cultivable area, GlobAgri-Agt finds a new equilibrium first evenly decreasing the level of its exports, and then if this is not sufficient, by increasing the level of its imports (see Supplementary material, for more information about the GlobAgri-Agt model). Using a world biomass balance model implies that only the biophysical impacts of scenarios will be assessed since economic variables such as input and output prices, income and welfare changes are not considered.

2.2. TYFA assumptions

The rationale and the technical parameters of the TYFA scenario are fully described in Poux and Aubert (2018) and Poux and Aubert (2022). In these papers, the authors show that the adoption of TYFA in the EU would lead to healthier diets reducing the risk of food-related diseases, a higher preservation of natural capital and biodiversity, lower GHG emissions and higher adaptation capacities of the agricultural sector to mitigate the effect of climate change. Similar to other agroecological scenarios, the main priorities envisioned by TYFA regard the closing of the nitrogen cycle, the extensification of crop and livestock production, the development of semi-natural vegetation, the limitation of non-food to food competition for the use of land, and the adoption of more sustainable diets. The assumptions related to each priority are summarised in Table 1.

The construction of the TYFA food regime as a EU average is based on the European Food Safety Authority references (EFSA, 2017), regarding macronutrients intake (carbohydrates and sugars, fibres, proteins, lipids, and fatty acids), supplemented with the French

TABLE 1 The main assumptions of the TYFA scenario.

Priorities in the TYFA scenario	Main assumptions
Closing of nitrogen cycle	• Phase-out of soybean imports
	• Reintroduction of legumes into crop rotations, including in cover-crops
	• High N fixation in extensive (not fertilised) permanent grasslands
	• Despecialisation of livestock and cropland areas
Extensification of production	• Removal of synthetic fertilizers and pesticides as farming inputs
	• Extension of semi natural vegetation and redeployment of natural/ permanent grasslands
Limitation of competition for land use	• Phase-out of biofuel and biogas
More sustainable diets	• Shift to healthier food regimes (lower energy and meat consumption, increased shares of fruits, vegetables, pulses, and coarse cereals)
	• Reduction of food waste by 10%

Agency for Food, Environmental and Occupational Health and Safety (ANSES, 2016) and World Health Organization recommendations, regarding the health risks and benefits related to the consumption of certain product groups. This food regime slightly decreases the current caloric intake at around 2,400 kcal/person/day and involves a strong reduction in animal proteins (−50%) and in the sugar content of the diet (−72%) (Poux and Aubert, 2018). As the TYFA scenario involves the preservation of extensive grasslands to favour a high level of agrobiodiversity and to provide fundamental ecosystem services (Dainese et al., 2019; Schils et al., 2022), the share of ruminant meat only slightly decreases. As the overall intake of meat halves, this results in a significant decrease in the share of poultry and pig meat, which nevertheless remain the most consumed types of meat in TYFA. In addition, the TYFA diet is rich in legumes because they are nutritionally sound, and they contribute to nitrogen provision in agricultural soils. Because of new technologies available in 2050 and a better management of losses at the production and consumption level, TYFA scenario envisages a 10% food waste improvement.

TYFA extensification of cropping systems relies on abandoning synthetic pesticides and fertilisers. The choice to abandon pesticides is connected to the improvement of health conditions for agricultural workers (INSERM, 2021), the decrease of the risk related to the presence of traces of pesticides in food, the protection of biodiversity (IPBES, 2016) and the decline of the emergence of crop resistances to new molecules (Hawkins et al., 2019). As far as synthetic fertilisers are concerned, their elimination contributes to lowering the risk of eutrophication, alteration of soil life, water contamination and fungal diseases and weed development in fields (Billen et al., 2011; Sutton et al., 2011). Furthermore, reducing fertilisation in cropping systems is a key element in climate change mitigation since nitrogen application to arable soils is one of the main factors contributing to agricultural sector GHG emissions. In such a perspective, the impact of organic fertilisers on GHG emissions in temperate areas is 2.6 times less important than that of synthetic fertilisers (IPCC, 2019). TYFA scenario also aims to phase-out soybean imports and reintroduce legumes such as peas, alfalfa, and fava beans into crop rotations. Despite, the big challenges that EU farmers will need to face to unlock a sector which is currently locked-in (Magrini et al., 2016), Guilpart et al. (2022) show that the agricultural area currently harvested is much lower than the area suitable for soybean cultivation and that the agroclimatic conditions would make possible to reach European self-sufficiency on soya in 2050. However, the reintroduction of legumes into crop rotations is not exempt from possible side effects. Legume production may lead to an increased reliance on pesticides when compared to cereals. Using more pesticides is clearly against the logic of the TYFA scenario. This means that a combination of genetic, agronomic, technological, and organizational innovations is needed to improve varieties, methods of plant protection and acquire better references on crop successions (Meynard et al., 2018).

Since TYFA cropping systems phase-out pesticides and synthetic fertilisers, they can easily be compared to current organic agricultural systems. For this reason, TYFA crop yields assumptions in 2050 (Table 2) were based on Eurostat data and current knowledge regarding the yield gaps between conventional and organic systems (de Ponti et al., 2012; Seufert et al., 2012; Guyomard, 2013; Ponisio et al., 2015). Following Ponisio et al. (2015) and Guyomard (2013), the reduction of 2010 yields in TYFA is in the order of −25% for cereals, between −20% and −45% for oilseeds and protein crops, −5% to −20% for fruits and vegetables and −10% to −15% for fodder and grass (Poux and Aubert, 2018).

TYFA assumes no further impact on crop yields due to climate change. The assumption is that the effect of water stress in Southern Europe is compensated by CO_2 fertilisation and projected rain regimes in Northern Europe, resulting in a balanced climate impact at the EU level. This modelling choice is consistent with the results of Makowski et al. (2020) for their scenario based on higher temperatures (+4°C), combined with a higher CO_2 concentration (+100 ppm) and the implementation of adaptation measures (−1.42 to +1.24% effect on C3 crop yields depending if a −10% rainfall decrease is considered or not).

An aspect which is only considered from a qualitative point of view in the TYFA scenario is the reduction of fossil fuels for agricultural production. Low inputs production methods are often criticised since they need a higher number of mechanised operations in the field to replace synthetic inputs such as pesticides (for example, soil tilling or mechanical weeding). Emissions related to energy consumption represent today around 7% of farm gate GHG emissions for the EU agricultural sector (FAOSTAT Statistics Database, 2016) and need to be reduced. This reduction can be obtained by switching to decarbonised sources of energy for tractors such as electricity from renewable sources or green hydrogen. Another option is limiting the share of heated greenhouses and relocate the production of fruits and vegetables to the areas having the most suitable soil and climate conditions. A condition for this shift will be the flexibility of EU consumers to purchase food products, which respect seasonality and the local availabilities.

TYFA livestock systems are characterized by a feed ration based on a limited use of concentrates and a higher amount of grass. Such

TABLE 2 Yield change for the main crops in the simulated scenarios.

	EU		Rest of the world (average)		
	2010	2050	2010	2050	
Crop yields (t/ha)	Initial (GlobAgri-Agt Initial situation)	TYFA-EU, TYFA-EU-Supply, TOGETHER	Initial (GlobAgri-Agt Initial situation)	TYFA-EU, TYFA-EU-Supply	TOGETHER
Crop yields not including climate change impacts					
Maize	6.7	5.4	5.2	8.7	5.8
Wheat	5.3	4.2	2.5	4.0	2.7
Rice	6.6	5.1	4.2	4.5	4.3
Other cereals	4.0	2.6	1.6	2.4	3.3
Soybean	2.6	2.3	2.5	3.2	2.4
Pulses	2.4	1.6	0.9	1.3	1.9
Sugar plants	67.1	54.4	68.6	91.6	73.5
Fruits and vegetables	14.8	11.9	14.3	19.6	24.8
Roots and tubers	29.2	26.3	13.0	16.1	14.6
Crop yields including climate change impacts					
Maize	6.7	5.4	5.2	8.0	5.8
Wheat	5.3	4.2	2.5	3.5	2.7
Rice	6.6	5.1	4.2	4.0	4.3
Other cereals	4.0	2.6	1.6	2.1	3.3
Soybean	2.6	2.3	2.5	2.6	2.4
Pulses	2.4	1.6	0.9	1.1	1.9
Sugar plants	67.1	54.4	68.6	103.8	73.5
Fruits and vegetables	14.8	11.9	14.3	17.4	24.8
Roots and tubers	29.2	26.3	13.0	15.3	14.6

feed ration contributes to reduce the competition between feed and food on cropland areas, increase the EU autonomy towards soybean imports (limiting possible future disruption of feed value chains, as the one experienced during the Ukrainian conflict, and imported deforestation), preserve grasslands, and produce omega-3 rich products with acknowledged nutritional benefits (Daley et al., 2010). Criteria such as the animal capacity to eat alternative source of fodder and the hardiness are privileged in ruminant selected species rather than physical productivity. The core of European livestock systems remains dairy production. Two dairy production systems coexist in TYFA and are configured based on Réseaux d'élevage et al. (2005), Coquil et al. (2014) and Barataud et al. (2015). The first one is a grass-fed system spread in medium- and high-altitude regions in which most of the fodder comes from permanent grasslands (5,000 kg milk/year). The second is a mixed system developed in wet plains, in which permanent grasslands are combined with temporary grasslands, cereals and legumes (5,700 kg milk/ year). Both systems involve the reintroduction of rustic varieties, a longer lifespan in animals (11 years for grass-fed, 9 years for mixed), the first freshening raised to 3 years and a lower replacement rate, which leads to a higher share of meat coming from heifers not intended for replacement which are slaughtered. Beef and sheep livestock systems follow the same logic as TYFA dairy systems with an extensified meat production and a feed ration, which is mainly grass-based (Chambres d'agriculture et al., 2014; Tchakérian and Bataille, 2014). The technical configuration of TYFA monogastric systems is based on the organic monogastric systems in Brittany (a region located in North-West France, which concentrates the largest share of French monogastric production) with specific feed rations for each stage of the production cycle (Bouvarel et al., 2013; Jurjanz and Roinsard, 2014; Bordeaux, 2015; Calvar, 2015).

2.3. Simulated scenarios

In addition to the reference scenario, we simulate three scenarios: TYFA-EU, TYFA-EU-Supply, and TOGETHER. We chose as our reference scenario the Metropolization_Ultrap scenario from the Agrimonde-Terra foresight (Le Mouël et al., 2018; Mora et al., 2020). In the reference scenario, both the EU and the rest of the world keep the on-going trends based on conventional intensification of agricultural production and the most recent nutritional transition in food consumption. In TYFA-EU, the EU fully adopts TYFA assumptions. In contrast, in TYFA-EU-Supply, we assume that despite the adoption of TYFA production systems, the EU consumers are not ready to change their energy-rich diets based on a high share of animal proteins, sugar and vegetable oils contained in ultra-processed food products. In TYFA-EU and TYFA-EU-Supply, the rest of the world remains on the pathway of the reference scenario. In the TOGETHER scenario, we test an agroecological transition involving agroecological production methods with a shift towards healthier food diets also taking place in the rest of the world. In TOGETHER,

assumptions for the rest of the world are an adaptation of those of the Healthy_AE scenario from Agrimonde-Terra.

The assumptions of the Metropolization_Ultrap and Healthy_AE scenarios borrowed from the Agrimonde-Terra foresight are fully described in Le Mouël et al. (2018). A detailed description is also provided in the Supplementary material. Main assumptions may be summarized as follows.

In Metropolization_Ultrap, every world region keeps the on-going trends based on conventional intensification of agricultural production. Technological solutions and intensification of chemical inputs allow to reduce the yield gap between current and potential yields (−50% on average). Because of induced technical change, this reduction is stronger for the crops which are the most grown in the scenario, such as primary cereals (maize, rice, and wheat), oilseeds and sugar crops, and lower for the other crops. In this scenario, the climate change affects the evolution of crop yields limiting the yield gap reduction for most of the crops and world regions (Table 2). Livestock systems also increase their efficiencies for both the ruminant and monogastric sectors. On the food consumption side, the past and current observed trends continue, which means an increased oils and sugar consumption in developed countries, increased caloric intake and share of poultry meat in emerging countries, and increased caloric and animal products intake in developing countries.

In Healthy_AE, agricultural production systems in the rest of the world evolve towards agroecology. We assume two different pathways of yield evolution. Differently from Le Mouël et al. (2018), developed regions such as North America, the European countries not taking part in the EU, or Oceania experience the same magnitude of crop yields reduction as the EU with the TYFA scenario. In contrast, in the same way as in Le Mouël et al. (2018), emerging and developing regions reduce their yield gap: −30% on average. Since these regions have a lower level of intensification of agricultural production systems than developed countries, we assume that the negative impact on yields of less intensive practices is limited and may be compensated by other positive impacts on yields such as those related to reduced loss on the production side resulting from continued technical change in harvesting and stocking equipment, transport infrastructure and logistics. In these regions, due to induced technical change, the higher demand of coarse cereals, pulses, fruits and vegetables and roots and tubers in Healthy_AE leads to greater than average yield gap reduction for these crops and lower than average yield gap reduction for other crops (including primary cereals and sugar crops). In this scenario, because of a collective effort on emission reduction, the objective of stabilisation of global warming is reached. For this reason, no impact of climate change on crop yields is assumed. Livestock systems are more extensive in Healthy_AE with a higher share of pastoral systems for ruminants and lower efficiencies for monogastric animals when compared to Metropolization_Ultrap. On the consumption side, the population adopts healthier food diets (maximum and minimum thresholds regarding the caloric intake, animal products, oils, sugars, fruits and vegetables and coarse cereals, for developed, emerging, and developing countries).

3. Results

3.1. TYFA-EU

In the TYFA-EU scenario, the agricultural land use in the EU remains at the same level as in the reference scenario (Metropolization_Ultrap) with almost no variations both for cropland (+0.3%) and pastureland (+0.2%) (Figure 1) (see Supplementary material for more information regarding the simulation results). This means that the effects of healthier and more sustainable diets completely offset the impact of TYFA assumptions regarding the reduction of agricultural productivity in the EU. The land constraint is respected, and no trade adjustment is needed to keep the agricultural areas inside the EU physical limits. When we take a deeper look at EU cropland, we observe a despecialisation of EU agricultural systems with crops that are currently marginal in EU agricultural systems taking a larger share of land use (Table 3). For pulses and soybeans in particular, the area expansion is particularly high and is a consequence of shifting EU consumer preferences on one hand (substitution of vegetable proteins to animal products) and of changing livestock feed rations on the other. For soybeans, the main reason explaining the rise of this crop production area is the phase-out of soybeans imports and the ban of synthetic fertilisers in the EU as prescribed by TYFA assumptions (Table 1). In terms of agricultural production, the lower productivity levels imposed by the agroecological transition drive down the volumes of EU vegetal (−35%) and animal (−48%) production (in calories) (Figure 2). For this reason, the EU reduces its share in world production and passes from 7% to 5% for vegetal products and from 12% to 7% for animal products. Despite this drop in domestic production, the EU can get its agricultural trade balance improved. While there is little change in exported quantities for vegetal and animal products with respect to the reference scenario (−5% and −1%, respectively), imported quantities substantially diminish because of lower domestic food consumption and the phase-out of soya import leading to a reduction by −58% for vegetal products imports and by −78% for animal products (in calories) (Figure 3). Therefore, the EU passes from being a net importer of calories to a position of net exporter of calories (net imports equal imports minus exports, when the balance is positive the country is a net importer while when it is negative the country is a net exporter). In terms of net import dependence (ratio between the net imports and total domestic use), the EU switches from a level of 5% in the reference scenario to −12% in TYFA-EU (Figure 4).

The other world regions (rest of the world) are only slightly influenced by the transformations of EU agri-food systems. The rest of the world land use remains at almost the same level as in the reference scenario (−2% for cropland and +0.3% for pastureland) showing the rather limited role that EU has in shaping the future world pathways. The same reasoning applies to the rest of the world production, which is only slightly impacted by EU changes: −2% for vegetal products and −1% for animal products. The production reduction in the rest of the world results from the decline of EU imports. For this reason, in TYFA-EU, the rest of the world reduces its exports (−7% compared to the reference scenario), while its imports remain unchanged. The exports of American and South-East Asian regions are the most sensitive to the EU agroecological transition. Since these regions are the main world exporters of soybeans and other oilseed products, they are the first world regions impacted in terms of net exports (−12%) mainly because of EU increased domestic production of protein crops.

3.2. TYFA-EU-Supply

In the TYFA-EU-Supply sensitivity test scenario, the assumption of unchanged food regimes makes the EU agricultural production no

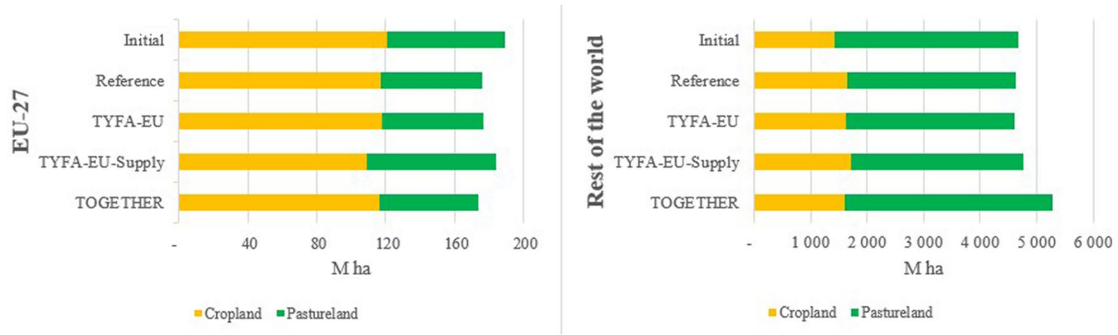

FIGURE 1
Land use in 2010 (initial) and 2050 for the simulated scenarios (million hectares).

TABLE 3 Relative change in land use between TYFA-EU and the reference scenario for the main cultivated crop categories in the EU.

Crop category	% Change
Fruits and vegetables	21
Grass	0
Maize, rice, and wheat	−11
Oilcrops	−53
Other cereals	4
Other forages	−3
Pulses	596
Soybeans	1,856
Sugar plants	−30

longer sufficient to cover EU food needs without expanding the initial level of EU cropland. Since this is not possible because we assume that the EU has already reached its maximum cultivable area in the initial situation, GlobAgri-Agt solving rules force the EU to decrease its exports and then to increase its imports, resulting in an increased EU import dependence. In terms of land use, while the EU cropland is unchanged, the pastureland increases with respect to the reference scenario (+28%). Indeed, as forages are not exchanged on the world market, the EU must produce its own domestic needs of forages, which are used to feed extensively the remaining domestic livestock (grass-like forage +44%, other forages +45%). In the meantime, the area employed to grow almost all the other crops decline, except for soybean production (+38%). Like in the TYFA-EU scenario, TYFA lower productivity levels affect the total output of EU agricultural production, which is lower in TYFA-EU-Supply than in the reference scenario. However, as the cropland is constrained while the pastureland is let to adjust freely in the model and the EU maintains food regimes, which are rich in meat and dairy products, the EU agricultural systems specialise relatively more in livestock production in TYFA-EU-Supply than in the TYFA-EU. The TYFA-EU-Supply vegetal production is lower than the TYFA-EU's vegetal production (−18%), while for animal production the situation is reversed (+50%). In the TYFA-EU-Supply scenario, the EU develops a large-scale soybean domestic production and becomes the fourth soybean-producing region in the world (16.5 million tons). Therefore, the EU can reach self-sufficiency for vegetable proteins, remove its dependence to protein imports and close its domestic nitrogen cycle, while maintaining diets rich in animal products. However, for balancing uses and resources the EU needs to increase the amount of imported calories with respect to TYFA-EU (+241%). Hence, the EU becomes a net importer of commodities such as dairy products, cereals, and pork meat for which it was previously a net exporter. The EU also develops a serious level of net import dependence (36%) reaching a similar dependence level as the one experienced today by North Africa and Near and Middle East (Le Mouël and Schmitt, 2018).

The rest of the world is impacted by the TYFA-EU-Supply scenario. Since the EU renounces to export in the world markets and increases substantially its imports, the rest of the world agricultural land use grows to cover for the EU lost export market share and increased imports (cropland +5%, pastureland +2%). For this reason, if compared to TYFA-EU, in TYFA-EU-Supply, the rest of the world production raises both for vegetal (+5%) and animal products (+3%). In terms of trade, since in TYFA-EU and TYFA-EU-Supply the rest of the world regions share the same food regimes, their imports remain constant. At reverse, the rest of the world exports grow for vegetal (+23%) and animal (+30%) products to offset EU declined export share and to provide food commodities such as fruits and vegetables, grains, oils, and sugar for the EU growing import demand. Rest of Asia, Former Soviet Union, Oceania, and Canada/USA are the regions which have a comparative advantage on these products, and, for this reason, they increase the most their net exports (+445%, +46%, +41%, +20%, respectively).

3.3. TOGETHER

In the TOGETHER sensitivity test scenario, the world population adopts healthier food regimes based on food diversity. The adoption of these diets reduces the global food demand and contracts the world market. For this reason, EU exports decline in volume relatively to TYFA-EU (−3% for vegetal products and −22% for animal products). The EU also experiences a change in terms of the types of products, which are traded. While in TYFA-EU the EU exported large quantities of wheat, sugar, dairy products, pork, and poultry meat, in TOGETHER it exports more coarse cereals, pulses, fruits and vegetables. Since the EU maintains the same food regime and the same agricultural systems as in TYFA-EU, the impact on land use (cropland −1%, pastureland −2%) and production (−6% for vegetal products

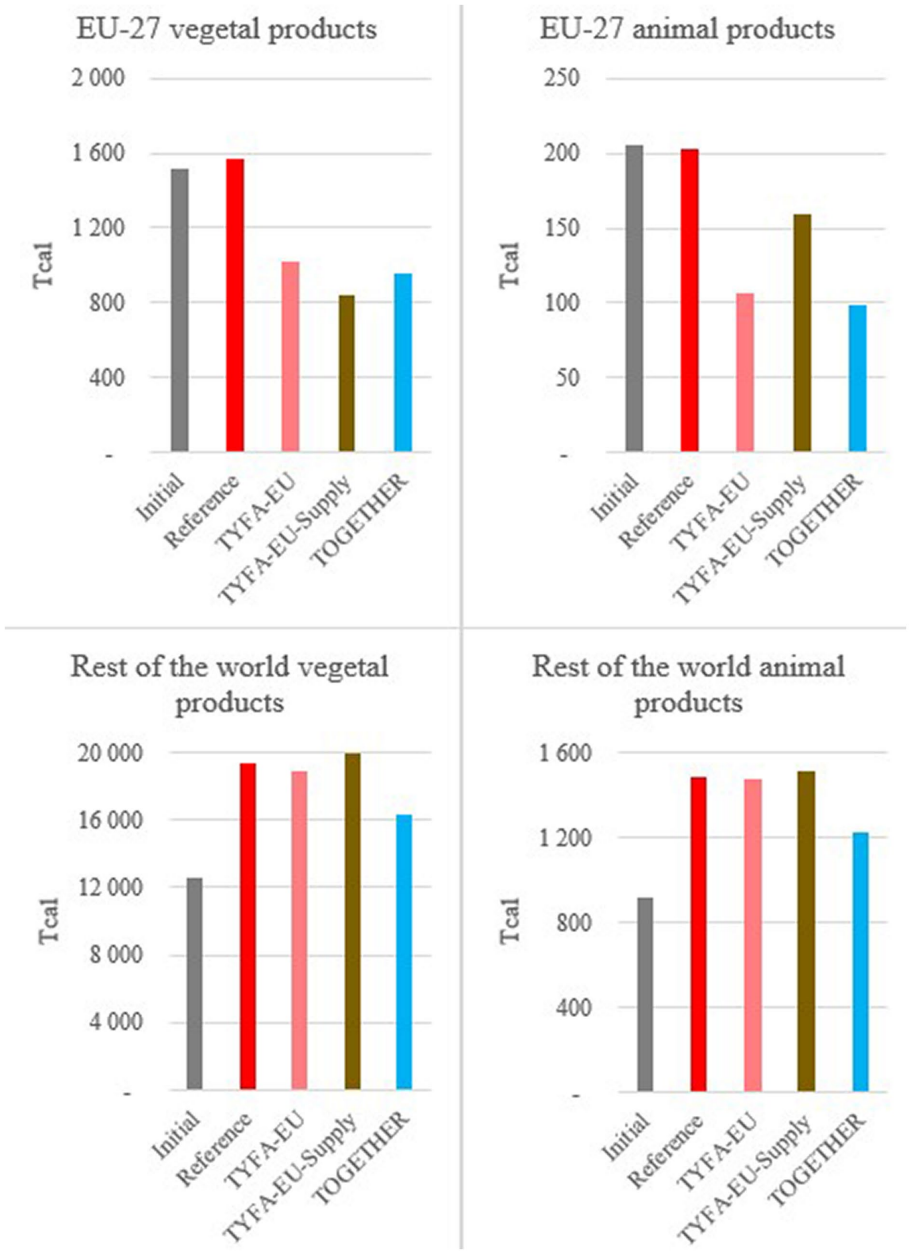

FIGURE 2
Production of calories in 2010 (initial) and in 2050 for the simulated scenarios (Tera calories).

and −7% for animal products) is only determined by the contraction of EU exports. Despite a reduction in the total amount of exported calories and a lower area of agricultural land, in TOGETHER the EU enlarges its export shares for vegetal and animal products in the world market passing from 8% in TYFA-EU to 10% in TOGETHER.

The rest of the world is deeply impacted by the TOGETHER scenario. When compared to TYFA-EU, the healthier food diets of developed and emerging countries lead to a reduction of world food production for vegetal (−14%) and animal products (−17%). This reduction is particularly strong in oilseed exporting regions (countries in South and North America and South-East Asia), which see their shares in world production reduced. In contrast, in developing countries in Sub-Saharan Africa and India, where adopting healthier diets implies consuming more calories, the production levels are similar as in TYFA-EU and substantially greater than in the initial situation. Because of lower yields and lower livestock production efficiencies with respect to TYFA-EU, the rest of the world increases relatively more its agricultural land use (+15%). The situation is very different for grassland (+24%) and cropland (−2%). The grassland expansion takes place especially in developing regions (Sub-Saharan Africa and India) where adopting healthier diets implies a higher consumption of animal proteins, partly obtained from grass-fed livestock. In reverse, the reduction of cropland takes place especially in oilseed exporting regions since the world demand of these products declines. The reduction of around a fourth of the rest of the world exports and imports of vegetal and animal proteins when compared

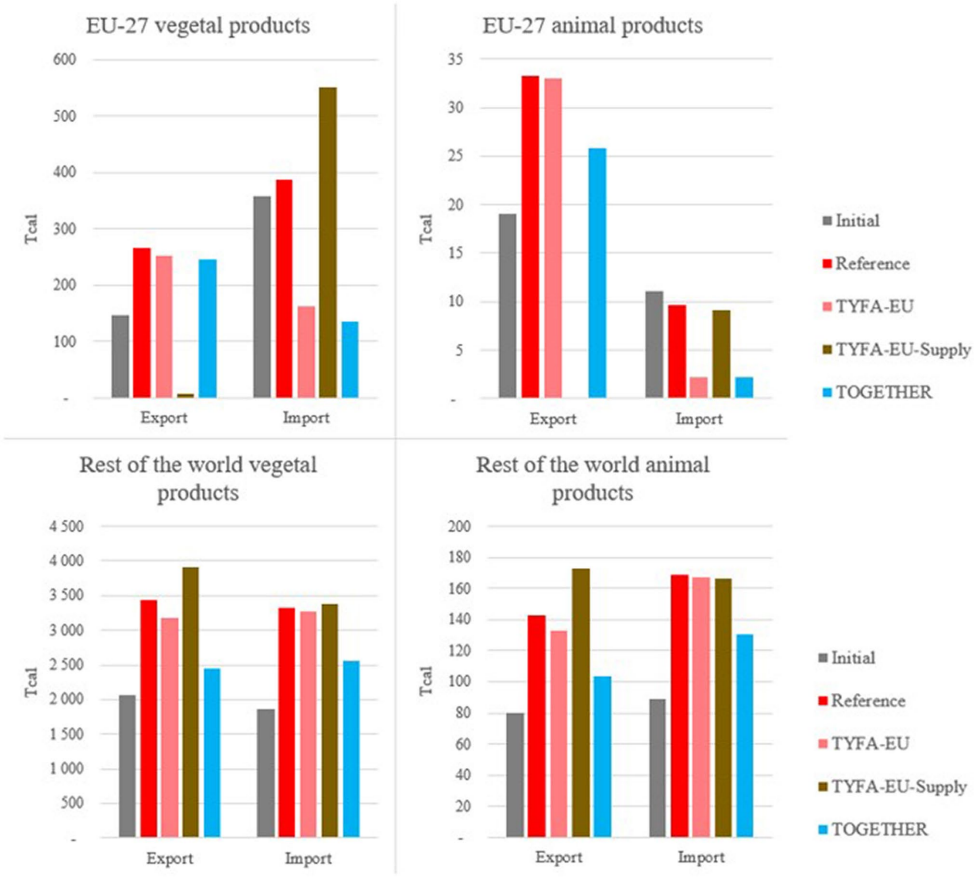

FIGURE 3
Exports and imports of calories in 2010 (initial) and in 2050 for the simulated scenarios (Tera calories).

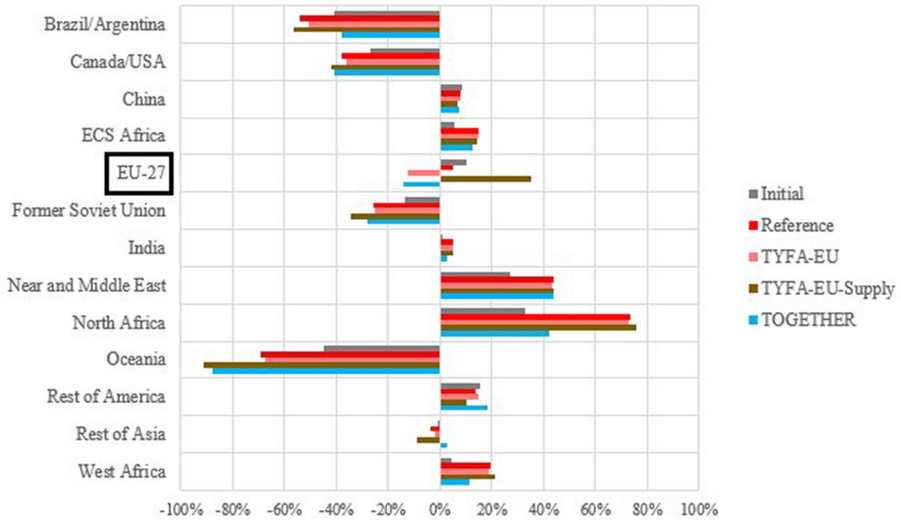

FIGURE 4
Net import dependence in 2010 (initial) and in 2050 for the simulated scenarios for each world region (%).

to TYFA-EU implies a reconfiguration of the world market. Similarly to what happens in the EU, the rest of the world increases its exports of fruits and vegetables, coarse grains and pulses, while the trade of all the other products is reduced. Differently from oilseed exporting countries in South America and South-East Asia whose export shares decline, regions such as the Former Soviet Union and Oceania

improve their trade balance mostly because of their comparative advantage in cereals production.

4. Discussion

4.1. The EU contribution to world food security

Our results show that from a biophysical point of view, an agroecological transition in the EU involving the adoption of healthy food regimes by EU consumers allows the EU to maintain unchanged its level of exports when compared to a business-as-usual scenario in 2050 without needing more agricultural lands. While the EU is initially a net importer of calories because of a high amount of vegetable protein imports used for animal feeding, results under the TYFA-EU scenario demonstrate that a full agroecological transition can allow the EU to increase its contribution to global food security becoming a net exporter of calories (Figure 5). Indeed, in this scenario, the level of EU exports is considerably higher than in the initial situation, in a future marked by a substantial growth of world food demand. However, as also mentioned in Tibi et al. (2020), the share of EU exports remains incomparable with the one of the main exporting regions such as Canada/United States, Brazil/Argentina, Former Soviet Union, and Oceania, which would be considerably higher than the one of EU in 2050.

In a context already marked by a risk of stagnation of crop yields (Brisson et al., 2010; Ray Deepak et al., 2012; Wiesmeier et al., 2015) and increased variability, and where plant breeding research is unlikely to compensate alone the lower agricultural productivity (Noleppa and Cartsburg, 2021), the results provided in this paper also prove that changing the current human diets is a compulsory aspect for the EU agroecological transition. TYFA-EU-Supply scenario shows that without such changes on the demand side, the EU would drastically increase its food dependence on global markets, which in turn contributes to the expansion of agricultural land in the rest of the world. The alternative to high food import dependence may be the extension of agricultural areas in the EU. Nevertheless, this also appears as a drastic solution as EU agricultural areas would need to grow by around 40% compared to the current situation, triggering negative effects on forest and grassland preservation.

In the TYFA-EU-Supply scenario, EU food import dependence increases, which limits the extension of EU agricultural areas and the induced threat to environment in the EU. However, this threat is exported to the rest of the world. Indeed, since the EU renounces to export on the world markets and increases substantially its imports, the rest of the world production grows, and the world agricultural land use raises relatively to the business-as-usual scenario. In a global context marked by conventional intensification of cropping and livestock systems, this would increase the pressure of agriculture on natural resources.

Finally, the TOGETHER scenario teaches us that the EU contribution to world food security remains unchanged in a scenario also involving healthier food regimes and deep transformations of agricultural practices towards more sustainability in the rest of the world. In this context, the EU adapts to the new world food demand changing the composition of its exported basket. The results demonstrate that this has no significant impact on the aggregate EU land use or trade balance. As also described in Mora et al. (2020), the main effects of this scenario take place in the rest of the world. One key result is the expanding grassland area in Sub-Saharan Africa where healthier diets mean an increase in the intake of animal proteins. Since deforestation is clearly against the pathway of TOGETHER, this means that further developments in efficiencies in livestock and agricultural production systems are likely needed in this region to preserve world forest areas.

4.2. Comparison with previous studies

In the last few years various studies analysed the potential impacts of transformative changes of European food systems. Beckman et al. (2020) and Barreiro-Hurle et al. (2021) using, respectively, a general and a partial equilibrium model of world agriculture, both simulated the impacts of the Farm to Fork and Biodiversity Strategies of the EU (F2F). Similarly to TYFA-EU-Supply, their simulated scenarios only consider the supply side targets of the EU Strategies, leaving unchanged the consumption patterns in the EU. The results of the TYFA-EU-Supply scenario confirm their findings: both scenarios find a potential drop of EU agricultural production, a decrease in EU export shares, and a rise of EU food import dependence, with induced higher agricultural prices and a potential threat to global food security. Since the tested assumptions in TYFA are more ambitious than the F2F targets (for example the phase-out of pesticides and synthetic fertilisers, while in the F2F the development of organic farming is limited at only 25% of EU agricultural land areas and the targets for pesticides and fertilisers use reduction are fixed at, respectively, −50% and −20% of current levels), the consequences of TYFA-EU-Supply are even more disruptive for the EU than the ones simulated in these two assessments. In Beckman et al. (2020) the production reduction is estimated at around −12% and between −15% and −5% in Barreiro-Hurle et al. (2021).

When we consider the TYFA-EU scenario, despite the drop of agricultural production, the shift in EU food regimes and the reduction of food wastes make the transition of EU farming systems not challenging for world food availability. Similarly, the compensating effect of decreased domestic demand in the TYFA-EU scenario prevents the transition of EU farming systems resulting in increased leakage effects in other countries (like in Henning and Witzke, 2021, where their sensitivity analysis shows the key role of the EU domestic demand for meat products). These results are aligned with the findings of Röös et al. (2022), Billen et al. (2021), and Tibi et al. (2020). Röös et al. (2022) demonstrate that the spread of local-agroecological food systems, involving lower-intensity cropping and livestock methods in half of EU cropland, the reduction of food waste, and the adoption of EAT-Lancet diets (Willett et al., 2019) by the EU consumers, allows the EU to spare more than half of its agricultural lands. The results of the scenario tested in Billen et al. (2021) indicate that from a biophysical perspective, Europe can relieve some pressure exerted by its current agricultural systems in the rest of the world if an agroecological transformation towards organic agriculture also involves a dietary change toward less animal products. In their scenario, the authors localise domestically the production of all oilseeds, fruits, and vegetables consumed by the European population,

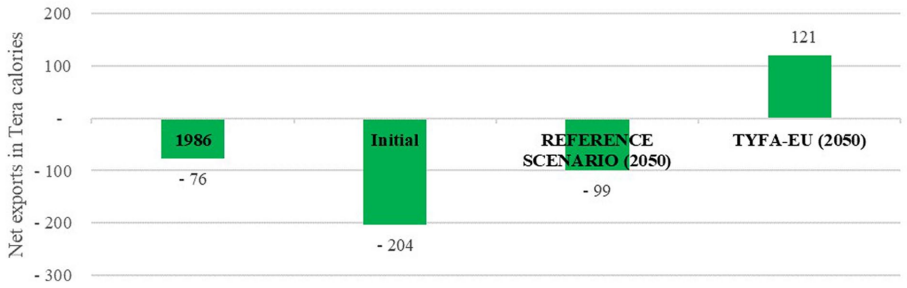

FIGURE 5
EU net exports in 1986, 2010 and 2050 under the reference and TYFA-EU scenarios. Treatment from FAOSTAT and GlobAgri-Agt model.

and obtain a positive Nitrogen net exports balance for cereals and animal products. In Tibi et al. (2020), despite more optimistic projected yield assumptions and lower changes in EU food regimes, the results show that in 2050 the EU could use part of its land surplus to increase the domestic production of protein crops and/or extensify its agricultural production systems, without reducing the amount of exported calories in the world market.

4.3. Policies to support EU agroecological transition

A multitude of studies show that changing food regimes based on sugar, fats, animal, and ultra-processed food products currently observed in developed and emerging countries, including the EU, is important from an environmental or public health perspective (see for example Tilman and Clark, 2014; Aleksandrowicz et al., 2016; Ridoutt et al., 2017; Springmann et al., 2018; Willett et al., 2019; Seconda et al., 2021). In this paper, we show that changing such food regimes in the EU is also key for maintaining the EU position in the world market in the context of EU agroecological transition. For this reason, policies aiming to change food diets appear as a precondition for EU agroecological transition. These policies can be divided in two groups. In the first group, we can find policies aiming to inform the consumer regarding the positive aspects of a healthy food diet. Examples of these policies are the launch of public education campaigns, the food labelling, the advertising regulation and the reinforcement of origin indications. The implementation of these policies may be relatively straightforward and do not require deep legislative changes. However, to be effective they need to be well financed and targeted possibly through participative activities (ex. nutrition education for pupils at school since the young age, cooking workshops in specific neighbourhoods etc.) (George et al., 2016). Similar to the policies of the first group is the creation of "nudges" which aim to softly change the food choice architecture using indirect conditioning or social norms to push the consumer towards a healthier food behaviour (Leonard et al., 2008; Wahlen et al., 2012; Ensaff, 2021).The second group of food policies embraces measures such as subsidies or taxes on food products (ex. taxes on unhealthy products, subsidies on healthy products, food stamps, VAT rate differentiation), the regulation of food canteens in schools and in workplaces. This last group of policies may certainly have a greater impact than policies in the first group. However, they are the ones, which risk causing the highest degree of public opposition because of their potential impacts on the cost of food and the perceived limitation of freedom of choice that some of these policies may impose.

When economic factors are considered, a scenario such as TYFA-EU appears riskier for the EU than a scenario like TOGETHER and would probably need a stronger policy support. In TYFA-EU, since EU food commodities are produced using agroecological techniques, they may result as more costly than the ones produced in the other world regions where farmers continue to use conventional agricultural methods. Consequently, EU farmers may implement a deep change in the structure of their agricultural production systems in order to respect environmental constraints and the planetary boundaries, but without having the certainty to be able to sell their high environmental value products in the world markets since they may be perceived as too expensive by other countries' consumers. Simultaneously, cheaper imports coming from geographic areas where growers have lower environmental and GHG emissions standards could overwhelm the EU domestic market. For this reason, in a current situation which is already marked by the decline of EU market shares (Schiavo et al., 2021), the maintenance of EU competitiveness appears as a prerequisite for the development EU agroecological transition. Several policies may be envisaged to reach this objective. In the first place, economic incentives aiming to boost the varietal research in diversification crops (ex. coarse cereals, legumes) can be mentioned. Results in this fields would make available for growers a wider range of varieties, which better resist to plant pests and diseases. Secondly, EU countries may adopt large-scale public investments to increase the potential of their circular economies. For example, additional sources of fertilizers coming from currently unexploited organic resources [for example home-sorted and market bio-waste, green waste and human excreta not already composted as advocated in Launay et al. (2021) and Billen et al. (2021)] could boost agroecological crop yields. Third, national and regional governments could also favour investments aimed at building new facilities to massify the national processing of diversification crops, achieve economies of scale and reduce transport costs (Schiavo and Aubert, 2020). Smaller and more versatile new storage facilities adapted to pulses, soybeans, and coarse cereals as well as new sorting equipment to favour the crop associations are example of tangible investments that policymakers may promote to support the transition (Magrini

et al., 2016). Finally, a period of temporary increase of taxes and tariffs seems necessary at least for the sector of protein crops. This market intervention could take the form of a tariff for specific food products coming from countries not complying with EU environmental standards or be inserted in a broader environmentally friendly scheme as the European Parliament and the Council carbon adjustment mechanism proposition (European Parliament and the Council, 2021). In both cases, these measures risk being considered not compatible with WTO rules (Bellora and Fontagné, 2022). However, this intervention would help EU farmers which are often subjected to more rigid environmental regulations than farmers producing in other parts of the world, but without being protected by trade measures. This period could be used by growers and processors to test innovations and develop new farming techniques to be competitive in the world markets even in absence of trade protection.

Supporting an ambitious agroecological transition such as the one simulated in our scenarios would also demand strong adjustments in the structure of the Common Agricultural Policy. In the short term, increasing the environmental criteria for having access to the Basic Payment Scheme could be a first signal sent to farmers to start considering a possible change towards more sustainability of their crop and livestock systems. In the medium term, more direct measures aiming to remunerate the ecosystem services may be necessary. Because of the specific ecological interest of protein crops, particularly legumes, the increasing of first pillar coupled aids can also be considered as well as the development of agri-environment-climate measures remunerating higher legumes shares in crop rotations. Increasing the budget of the eco-scheme jointly with the implementation of more environmentally ambitious rules regulating its access could encourage more farmers to implement the agroecological transition. Finally, the maintenance of grassland areas could be fostered through coupled aids directed to not fertilised pastures or through more indirect measures such as a carbon farming scheme remunerating carbon sequestration in soils (Bamière et al., 2023) or the restriction of livestock aids to pasture-based systems.

5. Conclusion

This study analysed the implications of a full-scale agroecological transition in the EU for the rest of world by 2050, and how the assumptions regarding the EU food regimes could impact the results. Due to the modelling tool used, we only assessed the consequences of this transition on the biomass balances of food products. Further work is needed to provide a broader impact assessment of the EU agroecological transition on economic indicators such as commodity prices, income, welfare changes, inside and outside the EU.

Despite these limits, our results reveal that an agroecological EU involving a shift towards more plant-based diets does not contribute to expanding agricultural lands, both inside and outside EU. Furthermore, such a transition would help the EU to contribute more importantly to global food security (at least from a biophysical point of view) by improving the EU trade balance in calories compared to the business-as-usual scenario. This finding remains consistent in an alternative scenario in which the rest of the world also adopts an agroecological pathway and healthier food diets. However, we also show that an agroecological transition taking place in the EU without corresponding changes in diets would lead the EU to drastically increase its food dependence on world markets and to contribute to the expansion of agricultural land in the other world regions.

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

MS, CLM, XP, and P-MA: conceptualization, methodology, and writing—review. MS and CLM: model development and writing. All authors contributed to the article and approved the submitted version.

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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

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1189952/full#supplementary-material

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Learning from the success of tobacco control: how to leverage ideas, interests, and institutions to reduce red meat consumption

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Over-consumption of red meat has significant impacts on public health and the environment. To achieve a planetary health diet, consumption of red meat must be reduced across the developed world. However, policy action on this issue has been lacking and there is insufficient research exploring how to overcome barriers to reducing red meat consumption. Using the 'three I's' policy change framework based around ideas, interests, and institutions and their influence on policy outcomes, this article will consider how the passage and success of Australia's tobacco control regime could provide lessons for achieving reductions in Australian red meat consumption. Drawing on stakeholder analysis through semi-structured interviews, this analysis demonstrates the explanatory power of the 'three I's' framework and highlights the essential roles of awareness-raising, cohesive policy networks, and a gradual increase in interventionism for achieving transformative changes in consumption behaviour. It also demonstrates the scale of barriers for policies aimed at reducing red meat over-consumption, and the potential policy windows that are opening due to a shift in meat consumption patterns.

KEYWORDS

planetary health diet, red meat consumption, food politics, food and nutrition policy, Australia

1 Introduction

The over-consumption of red meat above recommended levels is causing widespread health impacts including non-communicable diseases such as cancer and heart disease. At the same time, production of red meat[1] to feed the ever-increasing global appetite for steak is driving significant environmental impacts in terms of climate change, biodiversity loss, land degradation, and water use, as well as animal welfare impacts (Sievert et al., 2022). As such, there has been a call for a shift to a "planetary health diet" (EAT-Lancet Commission, 2020) which acknowledges

1 While the definition of 'red meat' can also include pork products, the environmental impacts of pork versus beef or sheep production are substantially different. As this analysis explores both the health and environmental impacts of red meat over-consumption, 'red meat' will from this point forward refer to meat from ruminant animals unless otherwise specified.

the co-benefits of reducing red meat consumption for both human and environmental health (Mehta-Bhatt and Ficarelli, 2015, p. 517).

While the need to address the over-consumption of red meat has been recognised and widely called for, there remains a lack of policy action. Likewise, research into the socio-political barriers for policies aimed at tackling red meat over-consumption remains scant (Intergovernmental Panel on Climate Change, 2015; Stoll-Kleemann and Schmidt, 2017; Sievert et al., 2021).

In terms of possible approaches for reducing the impacts of red meat consumption, there has been a focus on technological interventions on the supply side including methane-inhibiting feed additives for livestock and breeding and herd management mechanisms to address greenhouse gas emissions (Henry and Eckard, 2009; McGregor and Houston, 2018). On the consumption side, alternative proteins including plant-based meat and lab-grown meat have also been posited as pathways to reduce the environmental (and potentially health) impacts of red meat consumption (Sexton et al., 2019). There have also been suggestions for enhancing consumer awareness of the impacts of red meat to drive the shift toward healthier, more environmentally friendly products (Dagevos and Voordouw, 2013). Finally, it has also been posited that the use of a Pigouvian tax mechanism, such as a carbon price, may be the best option to substantially reduce red meat consumption (Bonnet et al., 2020; Perino and Schwickert, 2023).

However, what the existing literature lacks is sufficient analysis of the potential barriers to these policy interventions at the state-level, and opportunities for overcoming them. What is needed is an understanding of how other policies aimed at reducing the consumption of a popular product succeeded and an assessment of the views of stakeholders regarding these barriers and opportunities for red meat consumption.

One of the most successful anti-consumption policy interventions has been Australia's tobacco control regime (Studlar, 2005). It has long been held as an exemplar of effective health policy intervention, and numerous scholars have drawn the link between tobacco control (particularly its Pigouvian tax mechanisms) and potential learnings for addressing red meat over-consumption (Briggs et al., 2013; Bogueva et al., 2017).

This study has therefore been designed to consider how lessons from Australia's tobacco control regime could be applied to address red meat over-consumption. Australia was chosen as the case study due to being home to the world's most successful tobacco control regime (Studlar, 2005). Only 11.2 per cent of Australians smoke, compared to an average of 16.2 per cent in OECD countries (Australian Institute of Health and Welfare, 2023). Australia is also the third highest consumer of red meat in the world (Food and Agriculture Organisation, 2018), with Australians on average consuming 1.78 kg over the Australian Dietary Guidelines' recommended limit of meat each week. Colorectal cancer is the second most common cancer diagnosed in Australia, a large proportion of which is attributable to red and processed meat consumption (National Cancer Control Indicators, 2017). Grazing land encompasses 54.19 per cent of Australia's land mass (Australian Bureau of Agricultural and Resource Economics and Sciences, 2021), contributing to land clearing and degradation, and ruminant livestock produce at least 14 per cent of Australia's annual greenhouse gas emissions (Department of Industry, Science, Energy and Resources, 2018). As such, Australia presents an intriguing nexus of red meat over-consumption, red meat production, and has demonstrated success in policy interventions for consumption behaviours.

In this study, the three I's framework, which considers the influence of ideas, interests, and institutions on policy change (Poteete, 2003), is applied to explore the barriers that faced tobacco control in Australia, and how these were overcome. These lessons are then considered for the case of red meat over-consumption.

The three I's framework proves a useful explanatory tool for the barriers and drivers of policy change in the case of tobacco, and the potential learning opportunities for red meat. As posited by the theories of discursive and sociological institutionalism (Hope and Raudla, 2012), ideas prove to be the most significant barrier, but also the greatest opportunity to leverage change for both tobacco and red meat. Awareness raising is demonstrated to be essential for shifting discursive and normative barriers, and coordinated lobbying efforts are needed to combat the influence of vested interests. Policy precedent is also demonstrated as a valuable institutional tool for achieving sustained policy change. These lessons from Australia's tobacco control regime and how they apply to the case of red meat over-consumption provide much needed guidance on how barriers to policy action in regard to the planetary health diet can be overcome, both within and beyond the Australian context. Finally, a proposed policy matrix for reducing the impacts of red meat consumption inspired by Australia's tobacco control regime is presented as a potential path forward.

2 Materials and methods

Understanding policy change can be approached from a variety of lenses. One which is being increasingly employed is the three I's framework (Poteete, 2003). This approach draws from the theoretical contributions of public policy scholars such as John Kingdon (Béland, 2016) who acknowledge the interconnected role of material interests, institutional factors, and discourse in policymaking (Campbell, 1998). 'Ideas' within this framework are considered as shared beliefs, values, and norms (Pojani and Stead, 2014), and how discourse is mobilised in reflection of them. Policy can both mirror and be influenced by ideas, as they play an important role in the conceptualisation of policy and its legitimacy in the eyes of the public (Béland, 2016). 'Interests' represent a more traditional understanding of power mechanisms in policymaking, essentially those who have a stake (typically financial) in the policy and can influence the success of the policy overall (Campbell, 1998). While 'institutions' can include political institutions, legislative frameworks, policy networks, and policy precedent, playing a role in the establishment and enactment of policy (Lavis et al., 2002).

The three I's framework is grounded in the progression of policy studies through rational choice, to historical, sociological, and finally discursive institutionalism (Hope and Raudla, 2012) to explore how these three elements interact in policy stasis and change. However, the relative influence of each of these three factors in policy change remains in dispute (Kern, 2011). For instance, discursive institutionalists argue that ideas determine interests and shape institutions rather than being a separate phenomenon (Hope and Raudla, 2012). The application of the three I's framework in this study will contribute to this debate.

The analysis in this paper compares how ideas, interests, and institutions influenced the development of tobacco control policy in

Australia and how these lessons may (or may not) apply to the case of red meat over-consumption. For the case of tobacco, I draw on existing literature describing the development of tobacco control in Australia, supported by semi-structured interviews with three experts and advocates of tobacco control in Australia (see Supplementary material). For the case study of red meat consumption, the results from semi-structured interviews with 17 stakeholders in Australian red meat policy (see Supplementary material) are then considered in light of these lessons from the case of tobacco control.

Stakeholder analyses such as this are useful for testing the feasibility of policy instruments and determining the barriers and opportunities for action (Varvasovsky and Brugha, 2000). In this study, the stakeholders were selected through purposive sampling (Hibberts et al., 2012), determined based on their expertise in the areas of environmental, agricultural, and health policy in Australia, or their participation in the red meat industry. In total, 66 potential participants were contacted via email, of which 17 agreed to participate. Participants were interviewed face to face or over the phone between July and August 2018. The participant groups include red meat farmers, red meat industry representatives, and national and state level politicians. These stakeholder groups were selected due to their direct influence on red meat production, mirroring the approach of the only other stakeholder analysis on red meat consumption in the literature by Lerner et al. (2013). Nutrition and sustainability experts were also included for interview to provide additional context on the food policy arena surrounding red meat production and consumption in Australia (see Supplementary material). Their responses were thematically coded (Saldaña, 2021) using NVivo 12 against the three I's and corroborated with available literature on red meat in Australia.

3 Results

This results section will begin with a brief account of the path to success for tobacco control in Australia, considering the role of ideas, interests, and institutions. The learnings from this analysis will then be considered against the case of red meat consumption, drawing from the results of the stakeholder interviews.

3.1 Tobacco control and the role of ideas, interests, and institutions

Australia's gold-standard tobacco control regime emerged by overcoming beliefs and norms around smoking and challenging vested interests to achieve policy change. Through the strategic use of institutional factors, and the ideational shift against smoking that occurred in Australia, the tobacco control regime was able to succeed in substantially reducing tobacco consumption.

3.1.1 Ideas

Tobacco smoking was prevalent in Australia from the start of colonisation (Cancer Council Victoria, 2017). At their peak, smoking rates among men in Australia were at 72 per cent in 1945, and 33 per cent among women in 1976 (Winstanley and Woodward, 1995). Smoking could be seen at any hour of the day on streets, televisions, in bars and restaurants, and the home (Ballard, 2004).

The ideational shift against smoking began through increased public awareness of the health impacts of tobacco. This was triggered by the publication of landmark reports from the 1960s onwards by respected medical institutions and subsequent media attention and awareness raising campaigns by public health organisations (Chapman and Wakefield, 2001). The public became more aware of the impacts smoking has on health and as a result smoking rates among men declined from 58 per cent to 45 per cent in the space of 7 years (Winstanley and Woodward, 1995):

> *'[…] since then there's been a virtual explosion of the evidence on just how many diseases and how many cancers are caused by smoking. There's no doubt. It's probably one of the most solid facts in medical science that smoking is not good for you, so that's enabled campaigners to be very straight in the advocacy for measures to reduce smoking' (Tobacco-2).*

The success of these awareness raising efforts also challenged tobacco's cultural link with masculinity. Smoking was seen as an inherently masculine habit (Winstanley and Woodward, 1995), and tobacco giant, Marlboro, even created a sensual female brand mascot just to attract the Australian male audience. Smoking was associated with a strong, confident, 'outdoorsy' male image. However, the association between strength and virility and smoking was challenged as sporting stars joined with anti-tobacco campaigns to highlight the health impacts of smoking (Walker, 1984).

By the 1970s, general acceptance that smoking was bad for health was widespread (Chapman and Wakefield, 2001). Legislation including health warnings regarding smoking was introduced in 1969 and enacted in 1973. Tobacco advertising was banned across radio and television, and a national campaign against smoking was launched (Winstanley and Woodward, 1995).

However, momentum slowed as libertarian support for the right for individuals to choose to smoke prevailed. But this changed when new evidence came to light in the early 1980s regarding the impact of second-hand smoke (Ballard, 2004):

> *'Before that, it was: "Well, my smoking is dangerous to my health, but if I want to damage my health that's my business," whereas after that it was: "Well my smoking is also dangerous to your health," and so people have a right, according to the John Stuart Mill Principle of Liberty, to say: "Well you cannot. You can do what you like, but you cannot harm me."' (Tobacco-3).*

Prioritising the public good over the rights of the individual was the second key ideational shift for the Australian tobacco regime. The view that smoking was unhealthy was widespread, but this new evidence also made smoking anti-social, as it impacted the health of those around you (Chapman, 2007). This also represented a shift in the public's view on government intervention in individual lifestyle choices in the name of public health. Even today, after nearly three decades of one of the most comprehensive tobacco regimes, Australians are still in favour of even further intervention (Australian Institute of Health and Welfare, 2017).

3.1.2 Interests

One of the greatest barriers to tobacco control, even after the evidence came to light on tobacco's health impacts, was the tobacco

industry: '[…] incredibly well-funded to push in the other direction. And it's been fought all along the way. So the resistance has been enormous.'(Tobacco-1). Its lobbying efforts were relentless and powerful, involving some of the largest corporations in the world (McDaniel et al., 2008). The Australian tobacco market was US$21.72 billion (after inflation) at its peak (Cancer Council Victoria, 2018), so there was a lot to lose.

Following the ban on direct tobacco advertising in Australian media in 1976, the Tobacco Industry of Australia (TIA) was formed. A comprehensive force of publicists, media experts and lobbyists. The TIA held close ties with tobacco farmers, unions, the Media Council of Australia, and sporting groups. Sporting associations often lobbied on behalf of tobacco, due to threats that sponsorship would be pulled if any further legislation was passed minimising tobacco advertising. Similar fears of advertising revenue loss also led to lobbying for tobacco from Australian media moguls such as Kerry Packer and Rupert Murdoch (Ballard, 2004).

One of the main tactics used by tobacco interests was to discredit the scientific basis for anti-tobacco policies (Walker, 1984). The industry fuelled controversy around the impacts of tobacco on health, and funded scientists whose studies minimised the risks. In response to mandatory health warnings on cigarette packaging, the TIA argued that no further action was needed, as smokers had all the information to make an informed choice (Chapman, 2007). Tobacco industry efforts have continued even despite the success of Australia's anti-tobacco regime (as of 2019, only 11.6 percent of Australians smoked, down from 25 per cent in 1995) (Australian Institute of Health and Welfare, 2021). In 2012, when Australia became the first nation to introduce plain packaging on tobacco products, the tobacco industry challenged the decision in the Australian judicial system, bilaterally through investor-state arbitration, and multilaterally at the World Trade Organisation (Curran and Eckhart, 2017).

Political interests have also been a barrier for tobacco policy change. Governments supported Australian tobacco production for most of the 20th century (Freeman, 2016). In the 1980s, tobacco leaf production was the most heavily subsidised economic sector in Australia (Studlar, 2005). Tobacco farms were located largely in safe Country Party (now National Party) electorates, although some lay in important swing seats which helped perpetuate government support (Griggs, 2002):

> *'There were barriers that we had to overcome in terms of politics. Where, in the tobacco, there were several federal electorates, and state electorates for that matter, particularly in Queensland and Victoria, where tobacco is grown. In fact, that guaranteed a Country Party block, a small block that influenced parliament.' (Tobacco-1).*

Only in the wave of economic rationalism and neoliberalism from the late 1970s into the 1980s, and due to the significant costs of tobacco consumption on the public health system, did government support rescind (Ballard, 2004). By the 1990s, all tobacco farming in Australia was assisted by the Federal government to cease (Griggs, 2002).

Bridging the border between interests and institutions, Australia's anti-tobacco lobby was a key driver for the success of the regime. The anti-tobacco lobby was a coordinated and strategic coalition which collaborated for over 50 years and fostered some of Australia's most prestigious public health organisations (Walker, 1984). These groups were originally concerned members of civil society and non-government organisations which ran awareness raising campaigns and lobbied governments (Studlar, 2005):

> *'But with the legislation it became a matter of well, okay if you want legislation passed how do you do it? And you have to build up public demand for it. But also convince a small handful of people, they are known as politicians, that they have to, they should do this, and it would be a good thing to do rather than politically risky.' (Tobacco-3).*

Alongside the professional anti-tobacco partners were also more radical, but extremely popular, protest groups such as MOP UP (Movement Opposed to the Promotion of Unhealthy Products), and BUGA UP (Billboard Utilising Graffitists Against Unhealthy Promotions) (Ballard, 2004). Together, this coalition managed to drive the ideational shift against smoking described above, partly by utilising institutions to their advantage.

3.1.3 Institutions

Anti-tobacco networks developed links with public servants and health ministers to advance tobacco control. They put tobacco policy on ministerial meeting agendas, interpreted and reframed anti-tobacco messaging for political eyes, and worked closely through the formation of tobacco control legislation (Chapman and Wakefield, 2001):

> *'[…] we have also had – and this is really important – a small group of dedicated advocates who have stayed the course. So, one of the things that you notice about a lot of public policy issues is that people drift in an out, they do not stay the course' (Tobacco-2).*

One institutional element which was capitalised on by the anti-tobacco coalition, was Australia's federalised system. Australian states and territories have authority over policy areas including public health and agriculture, while the Federal government maintains jurisdiction over advertising restrictions and taxation. This led to a distinct pattern of tobacco control policy, with action emerging at the state level, often in more politically progressive states which were targeted by anti-tobacco advocates (Ballard, 2004). Policy diffusion would then lead other states to follow suit, increasing the de-normalisation of smoking and the normalisation of tobacco control. Even if Federal policy mechanisms such as taxation had the biggest impact on consumption, this came from the momentum of state action (Chapman, 2007):

> *'It's arguable whether we would have got as far if we had a single political system. Because, as you have already mentioned, one state will, you know, get a step forward and then everyone else will want to. Then the other people can say, "We cannot let New South Wales have that. We need that too."' (Tobacco-1).*

A final institutional factor which supported the success of Australia's tobacco regime was policy precedent. This allowed for the gradual scaling up of government intervention and the comprehensiveness of the regime. For instance, once governments

banned smoking in workplaces such as public service officers, it was difficult to justify why others, such as restaurants, still allowed smoking (Cancer Council Victoria, 2017):

> *'I'd say "Right, anyone been half pregnant?." And it's like, "What? You cannot be half pregnant." And I'd say, "Yeah well, this is an important political principle, and what it means is that when government acts incrementally so, for example, when they first banned tobacco advertising on television and radio; but not in print, cinema, billboards, sporting sponsorship, all of that; it allowed us to go 'well, you banned smoking on television because children saw the ads? Guess what, they also see them everywhere else."' […] And so that 'you cannot be half pregnant' principle allowed us to push the inconsistency of policy through.' (Tobacco-3).*

Other policies, such as drink driving, also provided the precedent for the prioritisation of the public good over individual liberty which was essential for the intervention into tobacco consumption (South, 1990).

3.2 Red meat and the barriers of ideas, interests, and institutions

Australia's tobacco control regime therefore succeeded through awareness raising of the impacts of smoking on smokers and those around them. This led to an ideational shift against smoking that provided the support for concerted lobbying by a coordinated and consolidated anti-tobacco policy coalition which drove policy change by capitalising on policy windows, diffusion, and precedent. In doing so, they overcame substantial ideational and material interest barriers which had embedded smoking into Australian culture.

So, what lessons can be gleaned from the tobacco case study for the case of red meat consumption? In terms of barriers to addressing the over-consumption of red meat, the stakeholders interviewed identified ideas, followed by interests, and institutions as the biggest constraint (see Table 1).

3.2.1 Ideas

One of the biggest ideational barriers to reducing red meat consumption, according to participants ($n = 12$) is that awareness is low among Australians of the health and environmental co-benefits of reduced red meat consumption. Despite highly publicised reports including the Food and Agriculture Organisation (2006)'s *Livestock's Long Shadow*, Australian consumers have been shown to still not understand the link between red meat consumption and climate change (Bogueva et al., 2017):

> *'People think climate change is about energy use, electricity, driving, and flights. And they do not realise that it's about food as well, and within that there's a big slice that's just beef on its own' (Climate-2).*

This is little surprise considering that the impacts of food systems are featured in less than 5 % of all media articles about climate change (Atkinson et al., 2023). Likewise, even considering the International Agency for Research on Cancer (2015)'s identification of red and processed meat as carcinogenic, consumers feel uninformed and unsupported in how to have a balanced diet whilst minimising meat intake, concerned about the loss of 'key nutrients' (Lea and Worsley, 2001).

This is likely influenced by the use of "nutritionism" (Scrinis, 2016, p. 17) by red meat advertising campaigns, which emphasise particular nutrients available in red meat to overemphasise its health benefits and convince consumers that it is the only source of these essential nutrients (The Campaign Palace and Meat and Livestock Australia, 2007):

> *'I think a lot of people just think "protein, protein's good." All Australians get enough protein. No Australians need more protein. And there's heaps of good sources of vegetable protein.' (Health-1).*

While red meat consumption can have health benefits, the campaigns do not specify how much red meat is recommended per the Australian Dietary Guidelines limit of 65 g of lean meat per day (National Health and Medical Research Council, 2013). Instead, they promote recipes and images of meals with red meat portions well over the recommended amount (Meat and Livestock Australia, 2015).

Industry funded research also became the basis for the Commonwealth Scientific and Industrial Research Organisation's Total Wellbeing Diet, a cookbook that emphasised a high protein (and red meat) diet. The book was purchased by one in ten Australian households (Meat and Livestock Australia, 2009) and nutritionists criticised the research for not testing the benefits of a more plant-based diet (Stanton et al., 2005).

In the case of tobacco, awareness raising on the individual impacts of smoking only supported reduced consumption to a degree. The key driver for the breadth of Australia's tobacco control regime was the impacts of second-hand smoking. For red meat, the argument for policy action for the sake of the public good is not so simple. A key difference between these two case studies is that from a health perspective, aside from costs to the health system from consumption-related disease, it does not harm those sitting next to you to eat a steak. The benefits for the public good are stronger in terms of the environmental impacts of red meat. However, red meat production is not the sole cause of climate change or biodiversity loss.

There is also the argument, raised by all farmers interviewed, that livestock farming can have positive environmental benefits through supporting soil carbon sequestration, and making use of otherwise unviable agricultural land ($n = 5$).

> *'I think that livestock management is a part of the solution to climate change in that, I think, essentially that farmers or people that are managing the land are in the perfect position to draw some of the carbon out of the atmosphere and store it in the soil where it originally came from and in trees and plants.' (Farmer-1).*

Likewise, even if all Australians reduced their red meat consumption to recommended levels, there may be no or minimal environmental benefit, as the majority of Australian beef and lamb is exported (Meat and Livestock Australia, 2020). Climate change policy is divisive enough in Australia for other emissions sectors (Macneil, 2016) without involving food consumption.

However, the lack of appetite for reduced red meat consumption is not simply due to lack of awareness about red meat's impacts. The

TABLE 1 Barriers to addressing the impacts of red meat consumption as identified by stakeholders.

		G1	G2	H1	N1	N2	C1	C2	C3	C4	C5	C6	A1	I1	F1	F3	F2	F4
Ideas	Eating habits/ culture ("It's unAustralian not to eat meat")	•	•	•	•	•	•	•	•	•	•	•	•	•				
	Knowledge and skills (cooking plant-based food, balanced diet)			•	•	•		•										
	Awareness (impacts on health, impacts on the environment)	•		•		•	•	•	•	•		•	•	•	•		•	•
	Meat is good for you									•				•	•			
	Gender ("real men eat meat")			•	•	•		•	•									
	Australian agrarianism (pastoral history, drover identity, farmers as land stewards)			•			•							•		•		
	Farmers are land stewards/ livestock as a climate solution									•	•		•		•	•		
Interests	Political impacts (rural seat, government overreach, unpopular policy)	•	•	•	•			•	•	•	•	•	•	•				•
	Economic impacts (cost to farmers, cost to rural economy, cost to low SES consumers, export oriented)		•	•						•			•	•	•	•	•	•
	Lobbies (MLA, NFF, meat processors)	•		•	•	•		•	•	•	•	•	•					•
	Social impact (impact on communities, need to retrain)									•			•	•				
Institutions	Policy precedent (pre-existing support for farmers)								•	•			•				•	•
	Lack of policy coalition		•					•		•	•	•						
	Inconsistent drivers (health, environment, animal welfare)		•							•	•		•	•				
	Institutionalised relationships	•		•	•													
	Carbon tax	•	•											•	•	•		

other most identified barrier by stakeholders was that it is 'unAustralian' to not eat red meat ($n = 13$):

> *'[…] you could see the front page of the Telegraph go "Ah! These crazy people, they want to destroy the lifestyle of Australians and stop us eating meat pies!"' (Greens-1).*

The Australian diet throughout its colonial history has centred on the British 'meat and three veg' (Lupton, 2000, p. 94). Pastoralism is embedded in the Australian colonial and cultural narrative ($n = 4$), and advertisements for early immigration to Australia boasted access to 'meat three times a day' (Baghurst et al., 2000, p. 3):

> *'I think that a lot of the barriers at the moment are cultural. So, this idea people have that meat is not, that a meal is not complete without meat in it; and that's going to sort of take a bit of unlearning to overcome that I think.' (Climate-1).*

Emblemising the Australian attitude to red meat consumption are the annual advertising campaigns by MLA, the peak red meat industry research and advertising body, released in the lead up to Australia Day. Beginning in the late 1990s, MLA launched a semi-ironic campaign starring ex-footballer turned comedian Sam Keckovich. Brimming with patriotic paraphernalia, the commercials degraded food from non-Anglo cultures, or anything plant-based, and emphasised that if you were 'Australian', you would be eating lamb on Australia Day (Ankeny, 2008). The campaign helped reverse a severe decline in lamb consumption, increasing it to its highest since 1985 (The Campaign Palace and Meat and Livestock Australia, 2007).

The cultural significance of red meat is also supported by the affiliation between red meat and masculinity in Australia ($n = 5$). Australian men are less likely to eat plant-based diets (Lea and Worsley, 2001) and more likely to associate them with weakness and femininity (Bogueva and Phau, 2016). The notion of 'man was made to eat meat' is a discursive tool used in advertising campaigns, suggesting that meat made 'man' strong, and enabled humans to evolve (Ankeny, 2008):

> *'If we look at what children, the sort of attitudes toward products, we find that little boys are given more meat than their sisters. So it's almost as if 'feed the man meat', 'meat is a man food' starts at an early age. So that is a problem, and one that we need to address.' (Nutrition-1).*

The ingrained role of meat in Australian food culture is exacerbated by a lack of knowledge and confidence of skills in cooking plant-based meals. This is a key barrier identified by health and nutrition stakeholders interviewed ($n = 4$) and demonstrated in research which shows that Australian consumers feel uninformed and unsupported in how to have a balanced diet whilst minimising meat intake (Lea and Worsley, 2001).

> *'[…] like the practical knowledge of knowing how to cook well with vegetarian or vegan meals. And, you know, being brought up often with meat as a staple part of the meal. And we know how to cook meals with meat, and most cookbooks are packed with meat diets, most celebrity chefs are doing mostly meat. So, you know, you go searching for recipes, you can find meat recipes, unless you go really looking for vegetarian meals.' (Climate-2).*

Unlike tobacco, we can live without smoking, but we cannot live healthily without a balanced diet. For consumers to reduce their red meat consumption they need to have knowledge and confidence in cooking meat-reduced or plant-based meals.

3.2.2 Interests

The combination of these ideational barriers presents a formidable task to shift norms, values, and discourse around red meat in Australia. Also standing in the way of this ideational shift is a significant pro-red meat coalition of actors with interests in high levels of red meat consumption.

The Australian red meat industry is smaller in terms of market value than tobacco was at its peak, but it nonetheless contributes AU$17.6 billion to Australian gross domestic product annually and either directly or indirectly employs 434,000 people (Meat and Livestock Australia, 2020). At its height, the tobacco industry only employed 6,000 people in comparison (World Health Organisation, 2002). These economic barriers were identified as key considerations by participants interviews ($n = 9$):

> *'It's not likely to be well supported in rural areas, for example, where people are involved in production of meat. They see that as their livelihood, and it is their livelihood.' (Greens-2).*

The red meat industry is also more diverse than tobacco, with over 75,000 businesses (Australian Taxation Office, 2016) versus tobacco's small number of foreign corporations, and as participants highlighted ($n = 11$), is represented by a set of powerful lobby groups. The official advocacy group is the Red Meat Advisory Council which works with other agriculture lobby groups, such as the National Farmers Federation (Meat and Livestock Australia, 2016). Also supporting the red meat industry is MLA as the marketing, research, and development corporation for the red meat industry. MLA's funding is supported on a dollar-for-dollar basis by the Federal government and farming levies, with an annual budget of AU$269.9 million (Meat and Livestock Australia, 2019). While MLA is prohibited from taking official positions on government policy, it plays an active role advising policy decisions and promoting the red meat industry:

> *'Meat & Livestock Australia are very powerful, and they are very powerful particularly when the Coalition is in government, because they are very good influencers on the National Party.' (Nutrition-1).*

Also involved in Australia's red meat industry are foreign companies such as Cargill and JBS, who each control 20 per cent of the meat processing sector (Ernst and Young, 2017). Cargill is one of the largest agribusinesses in the world and JBS is the world's largest meat processing company (Sojamo and Archer Larson, 2012). Policy action aimed at reducing red meat consumption in Australia therefore faces opposition from 75,000 red meat businesses, and these powerful multi-national corporations.

The red meat industry is also important politically ($n = 12$). For many rural communities, meat production and processing are an important source of income. In Dubbo, a regional centre in western New South Wales, the local abattoir is the town's biggest employer

(Australian Electoral Commission, 2010). This is not to mention the cultural significance red meat holds in Australia:

> *'I think people have, they feel they have an entitlement to eat red meat, Australian society in general. And if you remove that entitlement, then there'll be a whole heap, I do not think anybody would touch it politically because it would just be, you know, the uproar would be massive and they would just get booted.' (Agriculture-1).*

As such, none of the major parties at Federal or state levels have an official policy position aimed at reducing the over-consumption of red meat. Even the Greens avoid the subject (Greens-2), and all National Party representatives who were invited to participate in this research declined to be interviewed, further indicating political aversion to the topic. In 2008, the Federal government's Garnaut Review of Australia's GHG emissions recommended tackling livestock's contribution through an emissions trading scheme which would have had an impact on red meat prices (Garnaut, 2008). However, when the time came for the scheme to be implemented, agriculture was exempt (Department of Environment, 2014).

3.2.3 Institutions

Tobacco control faced a similar, though less formidable, coalition of pro-consumption interests. However, it overcame them partly through its consolidated and coordinated anti-tobacco network. Red meat, on the other hand, does not have a consolidated coalition of advocates for reduced consumption with a singular, consistent message ($n = 5$):

> *'I think any campaigns that go up against red meat will be driven by interest groups like animal rights group, perhaps AMA and similar medical groups, perhaps some environment groups who sort of see the net impact of this as sort of problematic in terms of their broader goals.' (Climate-4).*

Nutritionists interviewed, and public health groups in general, only advocate for reduced meat consumption in line with health recommendations. Environmental advocacy groups are mixed in their messaging, with some advocating for no meat, others a reduction, and some for 'better' meat such as grass-fed. There are also animal rights groups, who often use red meat's health and environmental impacts to encourage the complete removal of not only red meat, but all animal-based products from the diet (Laestadius et al., 2016). The lack of consistency in messaging and consensus among these groups makes for a mess rather than a coalition. These divisions are also reflected in consumers' differing motivations for reducing meat consumption (Cheah et al., 2020), making it difficult to garner united public support ($n = 5$):

> *'[…] there are two mindsets, and one mindset is that we need to do whatever we can to mitigate climate change and so that we are flexible. The other mindset is the mindset of a fundamentalist animal ethics person, and that is that we cannot kill animals.' (Agriculture-1).*

From an institutional perspective, this reduce-red-meat coalition also lacks networks with policy entrepreneurs which were so key for tobacco ($n = 3$). Instead, there is an institutionalised relationship between government and industry, as MLA is a government funded body whose role is to advocate for the red meat industry:

> *'[…] so many of them, you know, they receive money from the government and they really are lobby groups […] and they are lobby groups for just one section of farmers too. It makes it very hard.' (Greens-1).*

There is also a policy precedent of existing support for the red meat industry through subsidies and government grant programs, raised by several interviewees as potentially contradictory in the face of attempts to reduce red meat consumption ($n = 5$):

> *'I mean, it's sort of a tough call for a government to go up against, and essentially be seen as going up against an industry that, in other ways, it supports. So if you have got research and development money and various other things which you are going – drought subsidies, etcetera, billions of dollars there – which is going to support an industry, and then you take on that industry through a health campaign which says, "Do not eat red meat," sort of thing – it's actually pretty hard to reconcile in a political sense as well as a policy sense.' (Climate-4).*

The lack of success of previous carbon pricing mechanisms ($n = 5$), in addition to the existing controversies and tensions surrounding climate change policy in Australia (Macneil, 2016) are further policy precedents that could potentially impede efforts to reduce red meat consumption.

3.3 Opportunities for reducing red meat consumption

While there are formidable socio-political barriers to policies aimed addressing over-consumption of red meat in Australia, there nonetheless remain opportunities for policy action as shown by the stakeholder analysis (see Table 2) and demonstrated in the lessons from tobacco control.

3.3.1 Ideas

There are lessons in how tobacco control overcame barriers to policy change that are especially relevant for the case of red meat. While the majority of stakeholders identified Australia's meat-loving culture as a barrier, they also noted the changes to how Australians are eating as an opportunity for intervention ($n = 12$):

> *'I think the barrier of people sneering at people who did not eat red meat is really changing, it's changing really fast […] So I think that a lot of those, the social barriers are decreasing, the political barriers are not.' (Nutrition-1).*

For instance, as with tobacco, concerns around health have changed the consumption habits of Australian men. In the 1990s, the health impacts of saturated fat caused consumers, particularly men, to move away from red meat toward chicken which was perceived as healthier (Ankeny, 2008). While red meat consumption did eventually recover somewhat, it has never again reached the same consumption rates. More recent trends such as the popularity of the pro-veganism documentary Game Changers also mark a shift in the perception that red meat is central to the macho masculine image

TABLE 2 Opportunities for addressing the impacts of red meat consumption as identified by stakeholder.

		G1	G2	H1	N1	N2	C1	C2	C3	C4	C5	C6	A1	I1	F1	F3	F2	F4
Ideas	Eating habits/ culture (shift away from 'meat and three veg')	•	•		•	•		•	•	•	•	•		•	•		•	
	Knowledge and skills (cooking plant-based food, balanced diet)				•	•		•					•					
	Awareness (impacts on health, impacts on the environment)	•	•		•	•		•	•	•	•	•	•	•		•	•	•
	Reducing red meat for a balanced diet					•								•		•	•	
	Farmers as land stewards									•				•	•		•	
Interests	Subsidies and grants							•			•		•	•		•		
	Cooperative lobbies									•				•			•	
	Just transition	•	•					•										
Institutions	Policy precedent (dietary guidelines, ERF, sugar tax)				•	•		•	•			•	•	•			•	
	Research and development				•					•				•			•	
	Policy window										•	•						
	Availability of alternatives	•			•		•	•	•	•								
	Gradual increase in intervention	•	•		•			•	•	•	•			•			•	
	Carbon tax		•	•		•	•	•	•	•	•	•	•			•		•

(Morissy-Swan, 2019). As with tobacco, gender norms and associated consumption behaviours can be shifted with the right messaging ($n = 4$):

> *'[…] there is this link between meat and masculinity which needs to be broken. Because again, there is evidence that shows even the performance of men, that you perform better if you reduce the meat intake in your body.' (Climate-3).*

Likewise, the association between Australianism and red meat is also shifting. Australians increasingly enjoy meals with different kinds of meat, less meat, or sometimes no meat at all. Plant-based diets are more normal and accommodated for, with 12.1 per cent of Australians now eating plant-based most of the time (Roy Morgan Research, 2019). Even in MLA's advertisements, the messaging has shifted from xenophobia to inclusivity, with lamb just one part of a more varied spread of foods and cuisines (Hogan,

2018). This shift in Australian food culture was noted by several stakeholders as an opportunity to reduce over-consumption of red meat:

> *'[…] a lot of that is changing, it's much more acceptable to bring vegetarian products to a barbecue and to cook those as well. So it's I do feel like that culture is gradually shifting' (Climate-2).*

As with tobacco, awareness raising on the co-benefits of reduced red meat consumption is also a potentially significant opportunity for change. Almost all stakeholders ($n = 14$) supported increasing consumer awareness of the recommended amount of red meat per the Australian Dietary Guidelines and the use of consumer information tools such as a 'green star' rating or an ecological footprint as a signal for consumers:

> *'If we look at food, we can get cafes and restaurants, recipe books, top chefs, various people all sort of promoting plant-based food things. So, I think that promotion of this very happy, healthy, and delicious alternative is a real plus for doing this campaign. Compared with smoking which basically the message was 'do not', and here the message can go from 'less' to 'something more delicious, and healthier, and better for the environment'." (Nutrition-1).*

Farmers interviewed generally supported a 'less but better' approach, where livestock could be raised in a more sustainable and higher welfare manner, with farmers compensated through higher prices and society benefiting from the co-benefits achieved through lower consumption. This supported the desire from farmers interviewed to be compensated as environmental land stewards, rather than for maximising beef production:

> *'I mean, I think they'd happily do that. Because, the less stock you run, if you get a higher price per head, you know, you can do a better job anyways on your, you know, your ground cover and your native vegetation and even in a farm system, you could do a better job on those things.' (Farmer-2).*

Participants interviewed also advocated for more capacity building and awareness raising for plant-based cooking ($n = 4$). Interviewees cited initiatives such as the Stephanie Alexander Kitchen Garden National Program. Running in 10 per cent of schools, the program supports students to grow, prepare, cook, and eat plant-based foods. It has been demonstrated to encourage children to eat more vegetables and reconsider the need for meat to complete a meal (Yeatman et al., 2012).

Also noted by stakeholders was the increase in availability of alternative options to red meat through plant-based proteins. These reduce the learning curve for consumers and offer simple substitutions for red meat in familiar recipes:

> *'[…] for those that aren't ready to do that yet, then communicating to them that just cutting back on their red meat consumption can also have a really big impact, much better than doing nothing. And then yeah, again, just making sure the alternative products are up to scratch, and that there's enough on the market, and easy access, and at an achievable price point.' (Climate-1).*

Increasing awareness and availability of these options was cited as a valuable opportunity, however the potential health impacts due to the highly processed nature and nutrient profiles of some of these alternative proteins remains a concern (Sexton et al., 2019). As with tobacco and e-cigarettes, it is not preferable to shift to an alternative with unknown consequences (Jongenelis et al., 2018).

3.3.2 Interests

Regarding interests, a key difference between red meat advocates and the tobacco lobby is that organisations such as MLA are not wasting time on a denialist campaign ($n = 3$). The red meat industry representative interviewed emphasised the industry's support of limiting red meat consumption within recommended levels and acknowledged the environmental impact of red meat production (Industry-1).

In 2017, MLA announced its aim to make Australia's red meat industry carbon neutral by 2030. While this is not likely to reduce consumption, to achieve its goal there may be a need to reduce livestock numbers (Mayberry et al., 2018). The move also indicates that the industry could be open to other policies to address the impacts of red meat consumption ($n = 5$), and for government to capitalise on their institutionalised relationship with industry to support a just transition to a more diversified agricultural sector ($n = 3$).

3.3.3 Institutions

Building on policy precedent is also an institutional opportunity highlighted by some interviewees ($n = 8$). There was consensus on raising awareness of the *Australian Dietary Guidelines*, which for the first time in 2013 was successful in singling out red meat as a potentially harmful food (National Health and Medical Research Council, 2013), although this was included due to health rather than environmental concerns (Jones et al., 2019).

Health and nutrition stakeholders also pointed to the potential for a sugar tax in Australia as providing a precedent for similar Pigouvian tax mechanisms on other products harmful to health or the environment. Although, as demonstrated in the case of tobacco and noted by stakeholders, a pricing mechanism should not be the first port of call for policy intervention. Likewise, any carbon tax on red meat should be part of a broader carbon pricing strategy across all consumer goods.

Stakeholders agreed that a more gradual increase in intervention, similar to tobacco control, was a more suitable strategy ($n = 9$). Beginning with awareness raising, limitations on advertising, the use of consumer information tools, and a supported transition for industry.

4 Discussion

The results of this analysis demonstrate that ideas, interests, and institutions form an imposing set of barriers to policy change for addressing red meat over-consumption in Australia. Red meat differs from tobacco in terms of the scale of the norms, beliefs, values, and discourse which are embedded in Australian food culture. The fact that some meat consumption is still recommended for a balanced diet adds a layer of nuance that smoking never had. Likewise, the significance of red meat both for Australia's regional economies and

communities, and for its exports, poses a significant opposition force, without the consolidated coalition that tobacco had to confront it. Finally, the institutionalised relationship of red meat with Australian policymakers and the lack of policy precedent limits the policy windows for red meat compared to what was available for tobacco.

However, using the three I's framework to highlight the similarities and differences between the case studies of tobacco and red meat also indicates the opportunities for policy change to address red meat over-consumption, with lessons applicable to both Australian and international contexts (see Table 3). The stakeholder analysis (Reed et al., 2009) likewise identified areas of alignment and disagreement in terms of the perspectives and values of the stakeholder groups interviewed, as well as their relative interest and influence on the issue of red meat over-consumption (see Table 4). I will explore these findings further below.

Tobacco was ingrained in Australian culture, and particularly among Australian men. This was overcome through awareness raising and discursive tools such as evoking the good of the many over the individual to create an ideational shift against smoking. Red meat has also been a key component of Australia's food culture, especially for men, and this has been reinforced through advertising campaigns by the industry. Awareness remains low on the co-benefits of reducing red meat consumption, and consumers are also unsure of how to make the shift to a more plant-based diet. Nonetheless, Australian food culture is shifting away from high red meat consumption. This shift can be capitalised upon by emphasising the benefits a more plant-based diet can have for both health and the environment, as highlighted by Stoll-Kleemann and Schmidt (2017). As more plant-based protein alternatives come to the market, this transition should only become easier (Pointke et al., 2022).

Standing in the way of this shift, as was the case for tobacco, is a formidable group of vested interests who have much to lose if red meat consumption and production were to drop significantly, as highlighted also by Sievert et al. (2021). However, unlike for tobacco the red meat industry is more open to trying to address its impacts and there is an opportunity for a 'less but better' mentality to drive policy change (Resare Sahlin and Trewern, 2022). If this messaging were to be adopted consistently by the policy coalition of health, environment, and animal advocates campaigning for reduced meat consumption, then there may be even more of a chance of change.

The case of tobacco control also demonstrated how coordinated policy networks, taking advantage of institutional opportunities such as policy diffusion and policy precedent, can enable substantial policy change, as has been posited by Fesenfeld (2023). Through

TABLE 3 Summary of barriers and opportunities for policy action in tobacco versus red meat consumption within the three I's.

		Tobacco	Red meat
Ideas	*Barriers*	• Gender* • Australian identity*	• Gender* • Australian identity* • Concerns around health • Farmers as land stewards • Knowledge and skills
	Opportunities	• Concerns around health* • Impact on others	• Cultural influences on diet • Concerns around health* • Farmers as land stewards • Knowledge and skills
Interests	*Barriers*	• Political impacts* • Economic impacts* • Industry lobbies*	• Political impacts* • Economic impacts* • Social impacts for rural communities • Industry lobbies*
	Opportunities	• Anti-tobacco advocates* • Public support	• Financial support for industry to transition • Cooperative action by industry • Reduced red meat consumption advocates*
Institutions	*Barriers*	• Institutionalised support for industry*	• Institutionalised support for industry* • Lack of policy coalition • Inconsistent drivers (animal welfare, environment, health) • Climate policy legacy
	Opportunities	• Policy precedent • Policy coalition • Policy diffusion* • Policy windows* • Gradual increase in intervention*	• Research and development to support industry • Policy windows* • Policy diffusion* • Availability of alternatives • Gradual increase in intervention*

*Similarity between case studies.

TABLE 4 Stakeholder analysis of participant groups.

Stakeholder group	Interest	Influence	Perspective	Values
Farmers (F)	*High* – Concerns regarding implications for business cost and product demand, impact of climate change on production	*Low to moderate* – Farming sector in Australia is diverse and disparate, relies on industry representative groups to influence policy outcomes	• See a role for farmers as environmental stewards • Sceptical that consumers will be willing to reduce red meat consumption • Resistant to policy intervention but open to a 'less but better' approach	• Environmental resilience • Consumer preference • Quality produce
Red meat industry (I)	*High* – Concerns regarding implications for industry longevity and reputation, impact of climate change on production	*High* – Institutionalised relationship with government agencies, strong influence on policy formulation and outcomes	• See a role for farmers as environmental stewards and economic opportunities in better sustainability credentials for the industry • Open to policy support to reduce emissions • Comfortable with recommendations for red meat consumption within dietary guidelines	• Industry growth and resilience • Responsiveness to markets • Cooperative relationship with government agencies
Agriculture policy (A)	*High* – Desire a successful and resilient industry	*High* – Role in formulating policy and informing Ministerial decision making	• See a role for farmers as environmental stewards and economic opportunities in better sustainability credentials for the industry • Concerns around impact of climate change on productivity and communities • Sceptical of political support for policy intervention	• Industry growth and resilience • Cooperative relationship with industry • Minimising environmental impacts
Climate policy (C)	*Moderate to high* – Desire a resilient industry with a lower environmental impact, but less of a priority than other emissions sectors	*Moderate to high* – Role in formulating policy and informing Ministerial decision making but must be aligned with agriculture policy	• See a role for farmers as environmental stewards and economic opportunities in better sustainability credentials for the industry • Concerns around mitigation and adaptation in industry • Hesitant about direct policy intervention	• Minimising environmental impacts • Industry resilience • Minimising socio-economic impacts
Health policy (H) and Nutrition (N)	*Moderate* – Concerns around impacts of over-consumption of red meat, not main focus or priority over other foods such as sugar	*Moderate* – Role in formulating policy and informing Ministerial decision making, but limited opportunity for direct interventions	• Promote a 'less but better' approach and reduction of red meat consumption to within recommended levels • Open to alternative protein sources	• Enhancing health of population by ensuring a balanced diet
Greens Party (G)	*Moderate to high* – Desire a resilient industry with a lower environmental impact, but less of a priority than other emissions sectors	*Moderate to high* – Ability to influence policy decisions and outcomes, but only moderate influence on Government as a minority party	• No public party policy • Conscious of controversy and potential for backlash • Generally supportive of a resilient industry with reduced environmental impacts	• Improving environmental outcomes • Enhancing resilience of industry

designing and supporting a gradual increase in government intervention, consumption policy regimes can ultimately have an impact. Public health campaigns, labelling standards, environmental management, and agricultural policy all fall under the jurisdiction of states and territories. If red-meat-reduction advocates work toward consolidating their resources and their messaging, they could connect with policy entrepreneurs in more progressive states to push for policy change. This strategy was key to the success of the tobacco control regime and may lead to broader policy change in Australia if implemented.

Should such a policy coalition develop, there are a range of policy options available which could help to address the impacts of red meat consumption (see Figure 1). This policy regime should be implemented gradually over time, with a steady increase in the scale of intervention to ensure the greatest chance of success. On both the demand and supply sides of red meat consumption, there will be a need for:

1. Awareness raising: Enhancing understanding among producers and consumers of the environmental and health impacts of red meat over-consumption;
2. Building on precedent: Utilising policies and programs already in place, such as research and development on improving the environmental impacts of red meat production, and developing cooking skills among the Australian public to reduce meat consumption;
3. Enhancing consumer choice: Through labelling and certification mechanisms to direct consumers toward products with higher sustainability credentials and to further increase awareness;
4. Transitioning supply and demand: Supporting industry to transition into less emissions-intensive products and restricting advertising of red meat to limit over-consumption; and

FIGURE 1
Policy matrix for addressing the impacts of red meat over-consumption.

5. Addressing negative externalities: Through pricing in the environmental costs of red meat over-consumption via mechanisms such as a carbon price.

This policy matrix echoes the progression of Australia's tobacco control regime, giving time to build public and stakeholder support for increased policy intervention, and with it greater policy impact.

Nonetheless, tobacco and red meat remain somewhat of an apples and oranges comparison. The health benefits of totally removing red meat from the diet are not as clear cut as ceasing tobacco consumption. The analysis is also limited by its scope in using a state-level case study. There are shifting demands for meat occurring around the world. Notably, there has been an increase in consumption of poultry and pork, which have lower associated emissions although pork carries similar health risks to other red meats such as beef and lamb (Whitton et al., 2021). Nevertheless, demand for red meat in developing economies continues to climb, while red meat consumption in developed economies such as in Europe remains relatively stable (Ritchie et al., 2020) and typically above sustainable levels (EAT-Lancet Commission, 2020). The environmental impacts of red meat consumption are therefore not just linked to Australian eating habits, but also to broader dietary shifts occurring in some of the world's biggest meat importers such as China. Even if all Australians were vegetarian, the environmental degradation caused by red meat production would likely continue due to exports. The rise of alternative proteins further complicates matters, with ongoing debates on their health, environmental, and ethical credence (Sexton et al., 2019).

Meanwhile, alternative proteins, both plant-based and lab grown, are disrupting the red meat market (Sexton et al., 2019; Béné and Lundy, 2023). Red meat farmers are also pushing back against the perceived vilification of their industry, and utilising labels such as 'regenerative agriculture' to describe how red meat production can have a net environmental benefit (Bless et al., 2023). Some meat industry actors are also playing down the potential health risks of red meat consumption (Clare et al., 2022) and a lack of participation from Nationals Party politicians limits the ability of this study to explore appetite for addressing the impacts of red meat over-consumption across the political spectrum.

In terms of theoretical contribution, what this analysis has also demonstrated is that taking a more pluralistic approach to policy and political analysis is useful in understanding the interactions between material, cultural, discursive, and institutional dynamics in policy change. For both case studies, it was ideas, rather than interests or institutions, which was identified by interviewees as both the most significant barrier to policy change and promising opportunity for policy action. Interests were overall the main area of resistance, whereas institutions were the main grounds for achieving tangible change. This reflects the findings of those such as Hope and Raudla (2012) and Kern (2011) on the prominent role ideas play in policy change.

5 Conclusion

This study in its consideration Australian tobacco control helps address gaps that exist in the current literature regarding both the barriers and opportunities for policy aimed at red meat over-consumption. The stakeholder analysis provided important insights for where there is common ground among vested interests, such as in raising awareness of the benefits of keeping red meat consumption at a healthy level; as well as where contention lies, such as in the case of a carbon tax on red meat.

Furthermore, through the utilisation of the three I's framework, this study has uncovered a number of valuable policy insights regarding red meat over-consumption. This includes the necessity of a cohesive and strategic policy advocacy coalition, the value of awareness raising for enabling policy progression, and the importance of giving time to allowing the gradual build-up of interventionist policy mechanisms in order to avoid policy failure. These results also demonstrate the analytical and explanatory capabilities of the three I's framework.

However, given the evolving nature of discussions around red meat consumption, alternative proteins, and sustainable agriculture, there remains a need for ongoing research to keep pace with the ideas, interests, and institutions at play, and how best to achieve a planetary health diet.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by University of Sydney Human Research Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

AB: Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2023.1304179/full#supplementary-material

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Price above all else: an analysis of expert opinion on the priority actions to scale up production and consumption of plant-based meat in Brazil

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Introduction: Plant-based meats (PBM) are an emerging set of food technologies that could reduce the environmental impacts of food systems by mitigating consumer demand for animal products. However, scaling up the production and consumption of plant-based meats requires overcoming multiple technological, regulatory, political, and market barriers. An evidence-based prioritization of needs and actions may help actors (e.g., investors, funders, policymakers) who wish to help scale PBM achieve desired outcomes with limited resources.

Research question: What actions could most effectively help to scale up the production and/or consumption of plant-based meat in Brazil?

Methods: We selected Brazil as a case study of a country with a significant animal agriculture sector and a burgeoning PBM sector. We constructed a panel of nine experts and employed the Delphi technique during two rounds of an online survey to iteratively assess the degree of consensus and disagreement around the relative priority of 14 possible actions (identified from relevant literature) that could help to scale up the production and/or consumption of PBM in Brazil. We used the Importance, Neglect, and Tractability framework.

Results: The panelists collectively concluded that the top priority action for scaling up both the production and the consumption of plant-based meat in Brazil was to reduce the price of products for consumers. For most priority actions, there was greater consensus among panelists in the second round of the survey.

Discussion: Our findings contribute to an improved understanding of (a) which actions may be of highest priority for investors, funders, and policymakers, (b) synergies and differences between priority actions to scale up the production versus consumption of PBM in Brazil, (c) the relative merits of focusing on scaling up PBM production versus consumption, and (d) the strengths and limitations of assessing expert opinion on alternative protein futures using the Delphi technique.

KEYWORDS

alternative protein, consensus, cost, Delphi, effective altruism, policy, technology

1 Introduction

Animal agriculture has a significant environmental footprint, including on the climate and on land use. Livestock production is associated with a large proportion of the greenhouse gas emissions attributed to the global food system (Gerber et al., 2013; Xu et al., 2021), which in turn contributes about a third of total global greenhouse gas emissions (Crippa et al., 2021). Additionally, livestock production is a leading driver of deforestation (Steinfeld et al., 2006; Pereira et al., 2020), and land dedicated to grazing and animal feed production encompasses an estimated 50–78% of the world's agricultural land (Foley et al., 2011; Ritchie and Roser, 2019). Meat consumption is also associated with elevated risk of various human diseases (Papier et al., 2021) and with animal welfare concerns (Norcross, 2004; Heidemann et al., 2020).

Global shifts away from diets heavy in animal products toward more plant-based diets could help to reduce the environmental, human health, and animal welfare impacts of food systems. Many researchers, practitioners, and donors, including those concerned about climate change, land-use, and biodiversity loss, have advocated for broad scale shifts toward more plant-based diets that are less dependent on resource-intensive animal agriculture practices (Searchinger et al., 2019; Willett et al., 2019; WWF, 2020). Multiple interventions (e.g., policies, programs, technologies, behavioral nudges) have been developed and implemented to promote such shifts. Examples include national dietary guidelines that influence meat and dairy consumption (Behrens et al., 2017); greater availability of plant-based meals in college cafeterias to promote increases in vegetarian meal purchases (Garnett et al., 2019); self-monitoring text message campaigns using daily reminders on the health and environmental impact of meat consumption (Carfora et al., 2019; Wolstenholme et al., 2020); increasing the visibility and availability of plant-based products in supermarkets (Trewern et al., 2022); and production of plant-based substitutes for animal products (Apostolidis and McLeay, 2016).

Alternative proteins are an emerging set of food production technologies that could contribute to shifts away from animal agriculture by mitigating consumer demand for animal products. Alternative proteins include plant-based, cultivated, and fermented protein products that can be used as key ingredients in food products with sensory and nutritional profiles that closely mimic products traditionally derived from animals (Aiking, 2011; Tziva et al., 2020). These products comprise a new generation of products designed specifically to appeal to meat-eaters without the need to elicit major dietary changes (Tziva et al., 2020). If the production of alternative proteins scales up to account for a meaningful proportion of the total protein sector, these technologies could reduce the negative impacts of protein production on the environment (Tuomisto and Teixeira de Mattos, 2011; Goldstein et al., 2017; Poore and Nemecek, 2018; Springmann et al., 2018; Marinova and Bogueva, 2019), public health (Graça et al., 2019), and animal welfare (Santo et al., 2020). There is considerable uncertainty around the direction and magnitude of these potential environmental and health impacts of alternative proteins (e.g., Lynch and Pierrehumbert, 2019; Mariotti, 2023; Tay et al., 2023). Nonetheless, many stakeholders are sufficiently optimistic about the possible benefits of alternative proteins that they are heavily invested in scaling up the production and consumption of these food products (GFI, 2023a,b).

Plant-based meat (PBM) products are a class of alternative protein products derived from plant ingredients (Kyriakopoulou et al., 2019). PBM products generally have lower natural resource demands and environmental impacts as compared to animal-based meat products, including in terms of greenhouse gas emissions and land use (Smetana et al., 2023). PBM products can incorporate various plant proteins, including commoditized ingredients such as soy and pea protein as well as novel plant proteins with less well-developed supply chains (Kyriakopoulou et al., 2019; Ahmad et al., 2022). Functional ingredients (e.g., lipids, carbohydrates, flavors) from other plant sources are often added to improve the structural and nutritional characteristics of PBM products (Kyriakopoulou et al., 2019). PBM production processes typically involve protein isolation and functionalization, formulation, and various forms of extrusion and texturization (Rubio et al., 2020). Recent innovations in PBM product development include pretreatment procedures to improve functional properties and efforts to create products with enhanced nutritional compositions (Tachie et al., 2023). Global revenue for the PBM and plant-based seafood sector in 2022 was US $6.1 billion (GFI, 2023a).

Scaling up the production and consumption of alternative proteins, including PBM, requires overcoming multiple technological, policy, and market barriers (Stephens et al., 2018; Post et al., 2020). Such challenges include safety and regulatory hurdles (Hadi and Brightwell, 2021), consumer acceptance (Elzerman et al., 2011; Hoek et al., 2013; Bryant and Barnett, 2018; Graça et al., 2019; Malek et al., 2019; Siegrist and Hartmann, 2020; Onwezen et al., 2021), economic competitiveness with the animal-based meat industry (Ismail et al., 2020), and overcoming political influences that favor the incumbent animal-based meat industry (Vallone and Lambin, 2023). A range of factors affect consumer willingness and intent to purchase PBM, including demographics (Bryant et al., 2019), access to environmental and nutritional information (Chen et al., 2023), social norms and rituals (Jahn et al., 2021), and dietary preferences (Nezlek et al., 2023). Many of these factors vary by geography. As such, context-specific investment, innovation, policies, and research are likely needed to inform effective actions to overcome these barriers if alternative proteins are to achieve a meaningful scale and viable market traction.

An evidence-based prioritization of needs and actions may help any actor who wishes to scale up alternative proteins (e.g., investors, funders, policymakers) to achieve desired outcomes with limited resources. Funding, time, and labor are all finite, and resources to support the scaling up of alternative proteins are limited. Prioritizing resource allocation to actions that are likely to have the highest potential impact could help to maximize return on resources. Such an approach could also help reduce overall spending by forming a proactive rather than reactive resource investment agenda (Scherer et al., 2020). An efficient allocation of resources and effort could be aided by a systematic assessment of which actions would most effectively contribute to the goal of scaling up PBM production or consumption. While a growing literature (in part cited above) has characterized many of the barriers to scaling up alternative proteins, including PBM, we know of no research that attempts to quantitatively identify which potential actions to overcome these barriers are of greatest priority.

Questions about how to efficiently scale up the production and consumption of plant-based meat are of high relevance to stakeholders in Brazil, for multiple reasons. First, Brazil has a large animal agriculture sector that has both extensive environmental impacts and

nationally significant economic importance (Vale et al., 2019). Second, as global and domestic demand for protein increases, Brazil is predicted to remain one of the largest exporters and consumers of meat products (USDA, 2021). Third, Brazil has a burgeoning alternative protein sector, including a rapidly growing PBM sector (GFI Brazil, 2022). Brazil's plant-based foods sector (including PBM and seafood) reached approximately US $170 million in 2022, growing 42% from 2021 (GFI Brazil, 2023). At least 107 companies produce plant-based foods in Brazil and export to more than 30 countries (GFI Brazil, 2023). Approximately 14% of the total Brazilian population self-describe as vegetarian (SVP, 2022), and nearly 30% of Brazilian consumers have an interest in reducing their consumption of animal products (GFI Brazil, 2018). The stated intent of Brazilian consumers to eat PBM is influenced in part by how healthy, safe, and beneficial to the environment they perceived those products to be (Nezlek et al., 2023). PBM is now available in many Brazilian supermarket chains, although products tend to be more expensive and less widely accessible than animal-based meat (Reis et al., 2023). International non-profit groups have advocated for research to further develop the PBM sector in Brazil in consideration of the country's abundance of native plant species (Gallon, 2021). In combination, these factors make Brazil a globally significant actor in the past, present, and future of animal and plant protein production and consumption, and make it an important case study country to understand the opportunities and challenges associated with scaling alternative protein production and consumption. As such, in this paper we ask the research question: What are the actions that would most effectively help to scale up the production and/or consumption of plant-based meat in Brazil?

2 Methods

2.1 Case study: plant-based meat in Brazil

Our study focuses on plant-based meat rather than any other category of alternative protein products (e.g., plant-based dairy, cultivated proteins; fermented proteins) for several related reasons. We chose to analyze the potential of PBM as an alternative protein product that has relatively high market traction, and which is the focus of considerable investment and research in Brazil. We chose to focus on a single type and form of alternative protein product, because challenges and priorities likely vary dramatically between different *types* (e.g., plant-based dairy vs. plant-based meat) and *forms* (e.g., plant-based vs. cultivated) of alternative protein products. Therefore, each alternative protein type and form may face unique technological, policy, and market opportunities and barriers to scaling production and consumption.

2.2 Framework

We used the Importance, Neglect, and Tractability (INT) framework developed by the Effective Altruism (EA) movement (Todd, 2013). This framework was developed to prioritize causes and to compare alternative actions in terms of their potential impact. It can be applied to assess the value of allocating marginal resources to solving a problem or engaging in a particular action based on the importance, neglect, and tractability of that problem or that action (Todd, 2013; Dickens, 2016). In this context, an action is defined as: *important* if it would produce significant benefits, *neglected* if it is not currently being pursued or addressed; and *tractable* if it is likely to be successful.

2.3 Potential priority actions

We constructed an initial set of potential actions that could help to scale up the production and/or consumption of PBM. This list of actions was derived and synthesized from an amalgamation of barriers, challenges, and priorities identified in recent research papers and reports. We identified relevant peer-reviewed and gray literature using keyword searches (Supplementary Note S1) and a snowball approach. Some publications were particularly useful: for example, we drew on the future research opportunities identified by He et al. (2020) and the key actionable insights highlighted in The Good Food Institute's 2020 State of Plant-based Industry Report (GFI, 2020). We then reviewed the list and consolidated and clarified the candidate actions into a final list of 14 possible actions that may be considered priorities in helping to scale up the production and/or consumption of plant-based meat in Brazil (Table 1).

2.4 Expert panel

We used the Delphi technique to conduct iterative surveys to assess the informed opinions of a panel of experts. The Delphi technique is a method for gathering data from respondents within their domain of expertise and is designed to facilitate a convergence of opinion on a specific complex issue (Hsu and Sandford, 2007; Scherer et al., 2020). The Delphi technique provides panelists with the opportunity to reassess their initial survey responses after reviewing results from previous survey iterations (Figure 1; Hsu and Sandford, 2007). Advantages of the Delphi technique as a tool for expert consensus building include its capabilities to offer panelists anonymity, to reduce the effect of noise through a controlled feedback process, and to enable the use of statistical analysis in data interpretation (Hsu and Sandford, 2007). For example, when panelists provide quantitative data (e.g., scores, rankings), results from the Delphi method can be used to capture consensus by calculating the mean and standard deviation (Scherer et al., 2020). We solicited the panel members' perspectives on our primary research question: What are the actions that would most effectively help to scale up the production and/or consumption of plant-based meat in Brazil?

The principal inclusion criterion for an individual to qualify for the panel was self-declared expert knowledge, understanding, and/or experience relevant to our research question. We identified potential panelists through our own networks, and by asking for panelist suggestions from key individuals who worked in this area. We contacted a total of 21 individuals by email and/or via social media (e.g., LinkedIn). Thirteen individuals agreed to participate in the study, and all 13 responded to the round one of the Delphi panel survey. Four people did not respond to the round two and were thus lost from the study due to attrition. The final nine-person panel included four individuals whose primary affiliation was in the private sector (two working for PBM companies, two working as investors) and five individuals whose primary affiliation was a research institution (two at universities, three in public sector research agencies). All panel members had deep subject-area expertise on the topic of PBM in Brazil, either through applied research (including

TABLE 1 List of 14 potential priority actions to scale up the production and/or consumption of plant-based meat, identified through a review of the literature.

#	Priority action	Description
1	Protein sources	Identify new crops as viable sources of plant protein for PBM production.
2	Financial capital	Increase investment and funding for PBM production.
3	Start-up support	Improve access to technology accelerators, mentorship, and business support for PBM companies.
4	Sensory profile	Improve the sensory profile of PBM to more closely mimic their animal-based analogs.
5	New product types	Expand the diversity of PBM products available to consumers.
6	Manufacturing efficiency	Improve the efficiency of production facilities for PBM manufacturing.
7	Manufacturing facility capacity	Increase the number and/or capacity of manufacturing facilities for PBM production.
8	Level playing field	Alter the regulatory environment to create fair competition for alt-protein companies (e.g., create fair labeling laws, remove subsidies for animal products, introduce true-cost accounting for animal-based products).
9	Health, nutrition, and safety	Develop and adopt national food safety and quality standards for PBM products.
10	Price	Reduce the cost of PBM products for consumers.
11	Availability	Increase the availability of PBM products (e.g., by selling them in a wider range of retail outlets).
12	Visibility	Adopt strategies to leverage the consumer choice architecture environment (e.g., grocery store organization, menu order) to encourage purchasing of PBM products.
13	Marketing	Improve marketing strategies to promote consumption of PBM products.
14	Consumer acceptance	Reduce barriers to consumer acceptance of PBM (e.g., by influencing perceptions, attitudes, cultural norms).

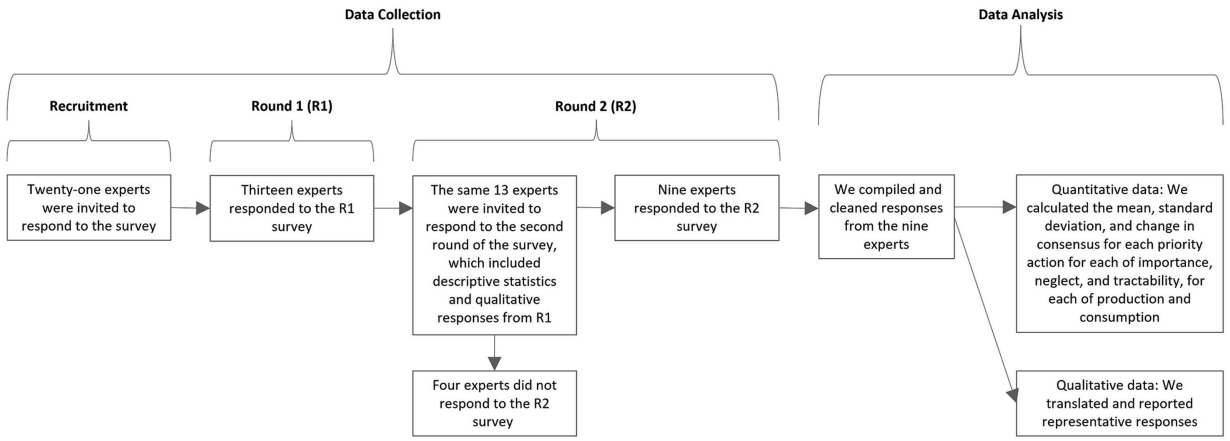

FIGURE 1
Schematic explanation of the methodology for this paper, including data analysis using the Delphi technique (involving recruitment and two rounds of an online survey) and data analysis of the quantitative and qualitative survey responses.

with multiple publications) and/or through active engagement in the development of PBM products.

In consideration of the time-intensive nature of the survey commitment (completion time for round one was estimated to be 20 min; round two additionally included the need to read the quantitative summaries and extensive qualitative responses of other panel members from round one), during the panelist recruitment process we included an invitation to be a co-author of the resulting paper as an incentive. This incentive was provided to aid recruitment and to reduce attrition between rounds, and to add additional expert insight to the framing and interpretation of the paper. We believe that any potential concerns about conflict of interest were mitigated by three actions: (a) we kept panelist identity confidential until after data collection was completed, (b) we allowed panelist co-author input into the Introduction and Discussion sections of the paper, but we restricted data analysis and the Results section of the paper to non-panelist authors, and (c) we offered no material incentives for survey completion. We observed precedence for including interviewees as co-authors in methodologically-similar papers (e.g., Kelly et al., 2019; Scherer et al., 2020).

2.5 Online survey

We developed and disseminated an online survey using Qualtrics™ software (Supplementary Note S2). The survey first collected information on the panelists' professional experience. Panelists were then asked to use a sliding scale tool to assign values

of 0 to 100 to the importance, neglect, and tractability of each of the 14 potential actions in relation to their role in helping to scale up the production and consumption, separately, of PBM in Brazil. For both production and consumption ranking activities, we instructed panelists to give the priority action that they considered to be most impactful a score of 100, and to evaluate the other actions relative to their top ranked action. Panelists were allowed to rank multiple actions as 100 if they felt they were of equivalent impact.

We conducted two rounds of the survey. The first round (R1) was conducted between February 21 and March 21, 2022. After R1, key data were summarized and shared with the panelists via email as required pre-reading ahead of the second round (R2) of the survey. The data shared ahead of R2 were: (1) the mean and standard deviation of the values assigned to each of the 14 potential actions (summarized in six dot plots, one for each combination of production and consumption, crossed with importance, neglect, and tractability), and (2) the de-identified, full qualitative responses from each panelist in response to the R1 question "Please provide a justification for your ranking decisions above" for each ranking exercise. Sharing the summary of key data from R1 enabled the panelists to read other panelists' responses and to adjust their responses in the second round if they were persuaded by anything that the other panelists said. In this way, the Delphi technique allows a form of asynchronous dialogue between the panelists. R2 was conducted between April 4 and May 5, 2022.

The first round of the survey was made available to panelists in both English and Brazilian Portuguese. All panelists elected to use the Brazilian Portuguese version, and so we developed the second round of the survey only in that language (Supplementary Note S3). We used the DeepL Translator software for translation in both directions, and a native Brazilian Portuguese speaker (RLMS) verified and, where necessary, improved the translation for all text where precise translation was critical (e.g., the survey, and cited quotes).

2.6 Data cleaning

We compiled the data in Excel and any identifiable information was first removed from each round of the survey. Next, each response was validated to ensure that respondents completed all questions and followed the instructions provided. Any incomplete or duplicate responses were then removed from the analysis. For any respondents that failed to rank any action as 100 in a particular exercise, their responses were rescaled relative to the highest score provided (see Supplementary Data S1, S2).

2.7 Data analysis

Data analysis was conducted in R (version 4.2.1) (Supplementary Data S3). For both survey rounds, we calculated the mean and standard deviation for the importance, neglect, and tractability of each action for production and consumption (Supplementary Tables S1, S2). We assessed consensus for each priority item by using the standard deviation (i.e., smaller standard deviations indicated more agreement and vice versa) after each survey round. To examine how consensus changed between R1 and R2 survey rounds, we subtracted the R2 standard deviation from the R1 standard deviation. A positive value indicated greater consensus in the second round (i.e., the standard deviation in R2 was less than in R1) (Supplementary Table S3). We report all values as rounded to the nearest integer, and thus report any consensus value between −0.49 and 0.49 as a zero change in consensus. We then created a prioritization score by averaging the importance, neglect, and tractability scores for each action for both consumption and production (Supplementary Table S4). We determined the final priority scores using only R2 data, since this was the final survey round and participants had considered the responses of other participants in R1.

3 Results

Here, we report the most and least important, neglected, and tractable actions, using the quantitative results from R2 of data collection. These findings represent the combined final rankings of the nine panelists, following two rounds of the online survey and following an opportunity to read each other's perspectives before responding in R2. The qualitative data used to illustrate the quantitative results are drawn from both R1 and R2.

3.1 Production

3.1.1 Importance

The potential action identified as being most important for scaling up production of PBM in Brazil was *protein sources* (mean ± SD score = 92 ± 7), which was described as "Identify new crops as viable sources of plant protein for PBM production." Second most important was *price* (89 ± 23), which was described as "Reduce the cost of plant-based meat alternative products for consumers" (Figure 2).

In relation to *protein sources*, several panelists highlighted the need for domestically sourced, Brazilian crop inputs. For example:

> "It is essential to ensure the country's sovereignty and sustainability in the production of raw materials for plant-based products."

> "Brazil is still very dependent on imported raw materials, except soy. The priority is to establish domestic options for vegetable protein and derived ingredients."

In relation to *price*, panelists commented that production would not be able to increase until the price was reduced and demand increased. For example:

> "To increase production, it will be necessary to increase consumption, both in higher and lower income segments [of society]."

Finally, at least one panelist connected these two issues, highlighting the interrelatedness of different barriers and priorities:

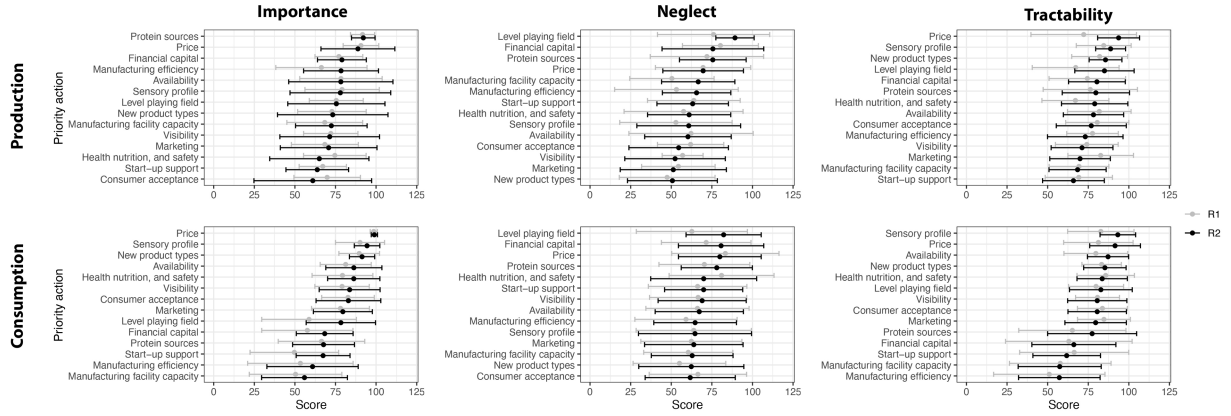

FIGURE 2
Comparisons between the importance, neglect, and tractability scores for each priority action to promote plant-based meat production and consumption in Brazil between Round 1 (R1, gray) and Round 2 (R2, black) from the Delphi analysis. Error bars represent the standard deviation, which we use as a proxy measurement of agreement among respondents.

> "In my view, the price is a very important factor for the consumer to choose the vegetable product. To reduce the price of products, it is essential to have local ingredients available. Today we have the limitation of very few ingredients: soy protein and peas, and the pea protein is imported. This makes the production cost very high, due to the exchange rate."

The least important potential priority action for scaling up production was *consumer acceptance* (61 ± 36), which was described for participants as "Reduce barriers to consumer acceptance of PBM (e.g., by influencing perceptions, attitudes, cultural norms)." The second least important potential priority action was *start-up support* (64 ± 19), which was described for panelists as "Improve access to technology accelerators, mentorship, and business support for PBMA companies."

Regarding *consumer acceptance*, one panelist claimed that this should not be a major concern, and rather returned to the importance of lowering the price of products.

> "I really think that the concern with consumer acceptance is of little importance, I believe that the current bottleneck is the price".

3.1.2 Neglect

The potential action identified as being most neglected in the scaling up of production of PBM was *level playing field* (mean ± SD score = 89 ± 12), which was described to panelists in the survey as "Alter the regulatory environment to create fair competition for alternative protein companies (e.g., create fair labeling laws, remove subsidies for animal products, introduce true-cost accounting for animal-based products)." The second most neglected potential actions were *protein sources* (76 ± 21) and *financial capital* (76 ± 31), which was described to panelists as "Increase investment and funding for PBM production."

In relation to the idea of creating a *level playing field*, one panelist noted that insufficient progress has been made on that front:

> "We have failed to achieve a level playing field for competition and production."

In relation to protein sources, one panelist observed that there had been little effort to establish domestic sources of key crop ingredients for plant-based meat:

> "It is unbelievable that we have to import cereals like peas for the production of plant-based meats in a country like Brazil, which has enormous productive potential. It is complex because this neglect needs to be changed by several actors, not only the plant-based meat industry itself."

Regarding *financial capital*, one panelist commented on the lack of investment in the plant protein sector, particularly in comparison to the conventional meat sector:

> "The neglect of capital investments in the plant-based meat industry becomes clearer when compared to the extent of sustained support for conventional meat production in Brazil."

The least neglected potential priority actions were *marketing* (51 ± 33) and *new product types* (51 ± 28), which were defined as "Improve marketing strategies to promote consumption of PBM products" and "Expand the diversity of PBM products available to consumers" respectively. Second least neglected potential priority action was *visibility* (52 ± 31), which was defined as "Adopt strategies to leverage the consumer choice architecture environment (e.g., grocery store organization, menu order) to encourage purchasing of PBM products."

3.1.3 Tractability

The potential action identified as being most tractable in scaling up production of PBM in R2 was *price* (mean ± SD score = 94 ± 13). Second most tractable was *sensory profile* (89 ± 9), which was described as "Improve the sensory profile of PBM to more closely mimic their animal-based analogs."

In relation to the tractability of *price* reduction, one of the panelists commented that investments in the production chain and product formulation will have a significant impact on the price:

> "Investment in the entire supply chain, scaling up raw materials and producing nutritious products will bring price reduction, thus leading to a definitive impact on consumption".

Regarding the tractability of sensory profile, one panelist commented that:

> "Indeed, sensory profile and price […] tend to be the most treatable to overcome in order to boost the market".

The potential action identified as being the least tractable for scaling up production of PBM in R2 was *start-up support* (66 ± 19). The second least tractable was *manufacturing facility capacity* (68 ± 18), which was described as "Increase the number and/or capacity of manufacturing facilities for PBMA production."

3.1.4 Range of responses

The range between the lowest mean value for any action and highest mean value for any action was smallest for the question of tractability of actions to scale up production (a 28-point gap). In comparison, this range was a 31-point gap for importance and a 38-point gap for neglect. This suggests relative indifference among the panelists as to which actions were more tractable than others. This sentiment was captured by one panelist:

> "The feasibility of most of the [actions] seems high to me, as long as there are investments to pursue the necessary advances."

3.1.5 Priorities

When importance, neglect, and tractability rankings were averaged, *price* emerged as the top priority action in R2 for scaling up production of PBM in Brazil (Figure 3; Supplementary Table S4). The joint second priorities were *level playing field* and *protein sources*. The lowest priorities were *marketing*, *consumer acceptance*, and *start-up support*.

3.2 Consumption

3.2.1 Importance

The potential priority action identified as being most important to scaling up consumption of PBM in R2 was *price* (mean ± SD score = 99 ± 2) Second most important was *sensory profile* (94 ± 8) (Figure 2).

Price was referred to repeatedly by panelists. For example:

> "Price is still a major impediment to the popularization of the products."

> "The consumer will increase consumption when the price is affordable."

Sensory profile was secondary, but also considered important:

> "Consumers who have a habit of consuming conventional meat will be willing to switch foods if they meet the sensory needs and price parity."

> "Plant meats should have adequate nutritional composition, but ensure that sensory characteristics (taste, texture, color) are similar to animal products."

The potential priority action identified as being the least important for scaling up consumption was *manufacturing facility capacity* (56 ± 26). The second least important was identified as *manufacturing efficiency* (61 ± 28), which was described as "Improve the efficiency of production facilities for PBM manufacturing."

3.2.2 Neglect

The potential action identified as being most neglected in the scaling up of consumption of PBM in R2 was *level playing field* (mean ± SD score = 82 ± 23). Second most neglected was *financial capital* (81 ± 26).

Regarding creating a *level playing field* to increase the consumption of plant-based products, a panelist commented that the allocation of investments and subsidies in the conventional (animal) protein sector is a constraint on the growth of consumption of the alternative protein sector:

> "Several other sectors are kept at a low rate of development because of this [constraint]."

In relation to the neglect of *financial capital* to increase the consumption of plant-based products, one panelist commented that:

> "[The country needs] to invest in better access."

The potential priority actions identified as being least neglected for scaling up consumption of PBM in R2 were *new product types* (62 ± 32) and *consumer acceptance* (62 ± 28). The second least neglected was *manufacturing facility capacity* (63 ± 25).

Regarding *new product types* and *consumer acceptance* as less neglected actions, two panelists commented that:

> "I believe that marketing and consumer issues are reasonably established and not so neglected"

> "The low score for consumer acceptance is because I believe it is already greater than product availability"

3.2.3 Tractability

Sensory profile was the potential action identified as being most tractable in scaling up consumption of PBM (mean ± SD score = 93 ± 11). Second most tractable was *price* (92 ± 16).

Regarding s*ensory profile*, one of the panelists commented that it needs to improve quickly, as it affects consumer acceptance:

FIGURE 3
Priority scores (+) for each priority action to promote plant-based meat production and consumption in Brazil, calculated by averaging Round 2 (R2) importance (•), neglect (▲), and tractability (■) scores from the Delphi analysis.

> "Initiatives in R&D, both public and private, will contribute more rapidly to the improvement of the nutritional and sensory quality of plant-based products, enhancing their acceptance by consumers."

Panelists offered ideas about how prices could be reduced, and why they thought that doing so was feasible. For example:

> "[Prices] can be significantly reduced with the increase of new raw materials"

> "Raw materials at scale, with nutritious products, will bring price reduction and therefore the impact on consumption will be definite"

The least tractable potential priority actions for scaling up consumption were identified by panelists as *manufacturing efficiency* (57 ± 26) and *manufacturing facility capacity* (57 ± 25), followed by *start-up support* (62 ± 21).

3.2.4 Range of rankings

The range between the lowest and highest mean values was smallest for the question of neglect of actions to scale up consumption (a 20-point gap), compared to importance (43-point gap) or and tractability (35-point gap). This suggests relative indifference among the panelists as to which actions were more neglected than others.

3.2.5 Priorities

For scaling up the consumption of PBM in Brazil, *price* was ranked as the top priority when importance, neglect, and tractability rankings were combined (Figure 3; Supplementary Table S4). The second and third priorities were *sensory profile* and *level playing field*. The lowest priorities were for *start-up support*, *manufacturing efficiency* and *manufacturing facility capacity*.

3.3 Changes in consensus: production

3.3.1 Importance

Between the two rounds of data collection, there was less participant consensus concerning the relative importance of most actions for increasing PBM production in Brazil (Figure 3; Supplementary Table S4). Ten out of the 14 total actions had less expert consensus in their second round rating as compared to first round ranking. *Consumer acceptance* (−16), *visibility* (−14), *level playing field* (−13), and *new product types* (−13) were the actions with the greatest decrease in consensus. *Manufacturing efficiency* (+5) and *manufacturing facility capacity* (+1) were the only actions with a greater expert consensus in the second round of data collection. There was no change in consensus for *financial capital* and *protein sources*.

3.3.2 Neglect

Ten out of the 14 total actions had greater consensus in production neglect rankings in R2 as compared to their R1 ranking (Figure 3; Supplementary Table S4). *Level playing field* had the largest increase in consensus (+23). *Manufacturing efficiency* (+17) and *protein sources* (+14) had the second and third greatest increases in consensus, respectively. *Visibility* (−18), *consumer acceptance* (−10), *marketing* (−10), and *financial capital* (−8) were the four actions that had less consensus in their production neglect rankings in R2 as compared to R1.

3.3.3 Tractability

Ten of the 14 total actions had greater consensus in production tractability rankings in their R2 ranking as compared to their R1 ranking, indicating that more consensus was reached for most actions. *Price* (+20) was the action that had the greatest increase in consensus, followed by *level playing field* (+8), *protein sources* (+8), and *sensory profile* (+8). *Manufacturing efficiency* (−7), and *consumer acceptance* (−2) and had less consensus in R2 compared to R1. *Health, nutrition, and safety*, described as "Develop and adopt national food safety and quality standards for PBMA products." and *visibility* had no change in consensus.

3.4 Changes in consensus: consumption

3.4.1 Importance

Between the two rounds of data collection, nine out of the 14 actions for increasing the consumption of PBM products in Brazil had greater consensus in their R2 ranking as compared to their R1 ranking. *Financial capital* (+11), *start-up support* (+11), *protein sources* (+8), and *level playing field* (+8) were the actions with the greatest increase in consensus regarding their importance for increased PBM product consumption. *Consumer acceptance* (−4), *availability* (−2), and *visibility* (−2) were the only actions with less consensus in the second round of data collection. *Marketing* and *price* had no change in consensus.

3.4.2 Neglect

Twelve out of the 14 total actions had greater consensus in their neglect rankings for increasing the consumption of PBM products in Brazil in their R2 ranking as compared to their R1 ranking. *Level playing field* had the most significant increase in consensus (+11), followed by *price* (+8), *protein sources* (+6), *start-up support* (+6), and *manufacturing efficiency* (+6). Only one action, *new product types* (−4) had less consensus in their consumption neglect rankings in R2 as compared to R1. *Health, nutrition, and safety* had no change in consensus.

3.4.3 Tractability

Greater consensus was reached for nine of 14 actions in R2 regarding their tractability for increasing PBM consumption in Brazil. *Start-up support* (+13) and *financial capital* (+13) were ranked as the most tractable actions for increasing consumption of PBM products, followed by *sensory profile* (+9) and *manufacturing efficiency* (+9). Five of the 14 total actions had less consensus in consumption tractability rankings in their second round rating as compared to first round ranking: *visibility* (−5), *consumer acceptance* (−3), *marketing* (−3), *level playing field* (−2), and *new product types* (−1).

3.5 Production vs. consumption

Panelists held a range of views on the relationship between production and consumption, and the relative merits and importance of focusing resource allocation to one or the other or both. Some panelists believed that production should be the focus since a greater scale is needed to drive down prices. For example:

> "As a priority, increased production can reduce the final price to the consumer, which is one of the biggest bottlenecks. Greater product availability also depends on increased production. In general, I understand that the biggest constraints are in production."

Others believed that consumption should be the focus, since without a strong market demand there was no possibility of scaling up production. For example:

> "I believe that to increase production … you first have to have products that meet the needs of a greater number of consumers. Before sensory and visibility aspects comes the need for competitive prices. Only then will there be a greater demand, requiring production increases."

Yet others felt that the two processes were deeply interconnected, and that it was not especially meaningful or possible to consider them separately. For example:

> "It's like asking 'which came first, the egg or the chicken.' The actions of production and consumption grow in parallel."

4 Discussion

4.1 Summary of results

Our nine panelists collectively concluded that the highest priority action for scaling up the production and consumption of plant-based meat (PBM) in Brazil was to reduce the cost of products for consumers. They identified the need to create a *level playing field,* described as to "alter the regulatory environment to create fair competition for alternative protein companies (e.g., create fair labeling laws, remove subsidies for animal products, introduce true-cost accounting for animal-based products)," as the second-priority action for production and the third-priority action for consumption. To increase PBM production, they collectively ranked *protein sources* as the third-highest priority action. For increasing PBM consumption, they collectively ranked *sensory profile* as the second-highest priority action.

Different actions emerged as the most important (i.e., *protein sources*), neglected (i.e., *level playing field*), and tractable (i.e., *price*) with respect to production. Similarly, with respect to consumption, *price* was the action identified as being most important, *level playing field* was the action identified as being most neglected, and *sensory profile* was the action identified as being most tractable.

Out of any of the total 84 values (14 actions, for each combination of importance, neglect, and tractability in relation to both production and consumption), the highest degree of consensus among panelists was that price was the most important action to scale up consumption. This action (i.e., decreasing the cost of PBM) received the highest mean value ranking (99) and the lowest variance (SD = 2) out of any of the total 84 values.

4.2 The future of plant-based meat in Brazil

Many actors in the public, private, and nonprofit domains are focused on developing the PBM industry in Brazil (Lazarin, 2022). The country has significant capacity and expertise in business, agriculture, technology, and supply chains. Some stakeholders have pointed to the high biodiversity of some of Brazil's biomes (e.g., Amazonia, Cerrado) as possible sources of novel raw materials for the production of PBM (GFI Brazil, 2021). Collectively, this nexus of skills and capital could help Brazil become a global forerunner in alternative protein production and consumption.

Price emerged as a clear focal priority for stakeholders interested in scaling up PBM production and consumption in Brazil. To the extent that priorities can be well-identified by our methodology and

the Importance, Tractability, and Neglect framework, reducing the cost of PBM products for consumers should perhaps therefore be a central focus of resource allocation. *Price* was ranked as the top priority action for scaling up PBM production and consumption, the most tractable production action, and the most important action for scaling PBM consumption in Brazil. This finding aligns with previous research that has found that Brazilian consumers are price-sensitive with respect to meat consumption (Hötzel and Vandresen, 2022) and that PBM tends to be significantly more expensive than animal meat in Brazilian supermarkets. On average, PBM products are 96% more expensive than animal products in Brazil (Reis et al., 2023) primarily due to costs associated with post-processing, production scale, and supply chains (Szenderák et al., 2022). PBM products are also less widely available than animal-based products, and less promoted through price reduction and multi-buy offers by retailers (Reis et al., 2023). Furthermore, Brazilian consumers tend to perceive PBM products as being much more expensive than animal products (GFI Brazil, 2018; Neto et al., 2020).

Prioritizing the reduction of PBM product prices may be especially important in Brazil and other low-and middle-income countries. Brazil is a middle-income country, with an average per-capita income of US$ 8,917 and with roughly 12% of the population living below the poverty line (World Bank, 2023). The average Brazilian consumer is likely to contend with a considerably more constrained food expenditure budget when juxtaposed with their counterparts in high-income nations, such as the United States and the Netherlands, where PBM products have gained substantial traction. These considerations may partially explain why the experts who participated in our panel considered reducing product prices critical to making PBM more widely accessible to Brazilian consumers. Furthermore, reducing product prices to encourage increased consumption was regarded by experts as a necessary precondition to scaling both the production and consumption of PBM products in Brazil. Increased PBM demand could stimulate increased sales volumes and the expansion of product offerings, which could facilitate further price reductions through economies of scale.

A focus on reducing product prices could help to create a clear objective for stakeholders interested in promoting the expansion of Brazil's PBM sector. For example, there could be opportunities for stakeholders to address some of the underlying causes leading to higher PBM prices present across different stages of the production supply chain (e.g., currently, a significant proportion of raw materials are imported; sourcing these ingredients domestically at scale may help reduce costs). Major meat processing companies in Brazil (e.g., JBS, BRF) may be best positioned to achieve rapid price reductions in consideration of their access to large-scale production plants, existing distribution systems, and relationships with retailers (Morais-da-Silva et al., 2022a; Reis et al., 2023). Smaller PBM companies and startups, in turn, may face greater difficulties in competing with meat processing companies' analogous products and entering into new distribution and retail channels. In addition, realizing significant reductions in PBM product costs within the short term may be challenging due to the typically higher manufacturing costs associated with PBM products in comparison to animal-based meat products (Morais-da-Silva et al., 2022a).

Reducing the price of PBM may increase consumer accessibility to these products. However, there is limited evidence to suggest that consumers would choose plant-based meat products over animal-based meat products, even if the two were comparable in terms of price, taste, and convenience (Peacock, 2023). Therefore, reducing product prices may not alone produce dramatic changes in production and consumption of PBM. Further, it is unclear whether price reductions would increase consumer willingness to actually *substitute* PBM alternatives for animal-based meats or whether price reductions would necessarily lead to substantive economic, environmental, or animal welfare gains. For example, PBM purchasing has not been found to deter meat demand among meat purchasing households (Neuhofer and Lusk, 2022). Another study found that decreasing the market cost of PBM meat by 10% could lead to a decrease in US cattle production of just 0.15% (Lusk et al., 2022). Relatedly, a study in Brazil found only very modest increases in fruit and vegetable consumption as a result of higher income, lower prices of fruit and vegetables, and/or higher prices of other foods (Claro et al., 2007). As a final example, data suggests that US consumers may purchase PBM primarily as a substitute for chicken, turkey, and fish rather than for more emissions-intensive beef (Zhao et al., 2023).

Creating a *level playing field* was identified as the most neglected action for scaling both production and consumption of PBM in Brazil. These findings support previous research identifying the need for adequate food policies to help guide a transition toward PBM products (Bryant and van der Weele, 2021; Newton and Blaustein-Rejto, 2021; Mancini and Antonioli, 2022; Morais-da-Silva et al., 2022a). In the EU and US, while some governmental initiatives have begun to support the alternative protein sector, powerful vested interests can maintain funding and regulatory environments that favor animal agriculture (Vallone and Lambin, 2023). Bringing more attention to the action of creating a level playing field could require engagement from policymakers to identify and reform policies that may be contributing to an unlevel playing field for PBM products. Policymakers could address any such policies that foster inequities between the PBM and animal agriculture sectors. To maximize Brazil's potential socio-economic benefits from the growth of the PBM sector, policymakers could develop national and/or regional plans customized to the natural resources and human capital in specific geographic regions (Morais-da-Silva et al., 2022a). It is currently unclear whether policymakers in Brazil are motivated to create a level playing field for PBM products, and stakeholders from the country's animal agriculture sector may be resistant to policy change. Non-profit organizations or advocacy groups in Brazil could help to scale up production and/or consumption of PBM by lobbying for policy change and communicating to consumers the potential benefits that PBM products could offer. Of course, interpretations of a level playing field may vary among various actors, and the potential exists that some PBM advocacy groups could overcorrect and excessively favor alternative proteins in their pursuit of rectification.

Identifying new protein sources emerged as the most important action for scaling up PBM production. This action has previously been identified as a high-impact opportunity for Brazilian agricultural producers in light of the abundance and diversity of native and introduced plant species (e.g., lupin beans, faba beans, and rapeseed oil) in PBM production (Kyriakopoulou et al., 2019; Morais-da-Silva et al., 2022a). Some work has been initiated to tackle this action. For example, there has been investment into research to identify indigenous sources of Brazilian plant protein from the Amazon and

Cerrado biomes (Gallon, 2021). In addition, it may be necessary for Brazilian agricultural producers to adapt their practices in compliance with GMO-free standards and develop new processing plants to render new protein sources suitable for incorporation into PBM products (Morais-da-Silva et al., 2022a).

Finally, improving the *sensory profile* of PBM products to more closely mimic their animal-based analogs was identified as the most tractable action to scaling PBM consumption in Brazil. Although the sensory profiles of PBM products have become increasingly similar to animal meat products, the taste and texture of PBM remains a potential barrier to acceptance by Brazilian consumers (Morais-da-Silva et al., 2022a). Health, safety, and nutrition are key attributes that affect consumers' willingness to purchase plant-based products in Brazil (Gómez-Luciano et al., 2019). Improving the sensory profile of PBM to increase consumer acceptance may involve reducing undesirable flavors sometimes associated with plant ingredients, such as a beany flavor, bitterness, or astringency (Wang et al., 2022). Other opportunities to improve the sensory profile of PBM products include using genetically engineering microbes to produce fat with melting points comparable to the melting point of animal fat, or using fungi-based products to improve the structural and fibrous quality of products (Tachie et al., 2023). Finally, PBM could be blended with animal meat or with other alternative proteins to create better-tasting products (Grasso et al., 2022).

Collectively, these findings suggest that stakeholders could most usefully direct resources to reduce PBM product costs, improve the sensory experience of PBM products, and champion the creation of a regulatory environment that creates fair competition for alternative protein companies. The actions panelists ranked as the highest priority align with previous research on opportunities to increase PBM production and consumption in Brazil (Morais-da-Silva et al., 2022a,b; Reis et al., 2023).

4.3 Scaling up production and consumption

Among the 14 potential actions examined in the study, some exhibited a stronger emphasis on the production side of the supply chain, such as improvements in manufacturing efficiency and manufacturing facility capacity. In contrast, others were oriented toward the consumption side of the supply chain, such as marketing and consumer acceptance. We initially expected that very different actions would be prioritized, depending on whether a stakeholder was responding, within our survey, to questions about how to promote PBM *production* or *consumption*. For example, *in principle* Brazil could become a globally significant export producer of plant-based meat. With a strong export market, it may be less of a priority to promote demand among consumers in Brazil. Conversely, *in principle* Brazilians could consume large quantities of PBM, with demand met through imports from the US and elsewhere. In such a scenario, Brazil's PBM production could remain relatively limited. *In practice*, it appeared from our data that many Brazilian stakeholders involved in the PBM sector are invested in increasing both production and consumption within Brazil, simultaneously.

We expected that production-focused actions would emerge as the priorities for scaling production, and that consumption-focused actions would emerge as the priorities for scaling consumption. However, our results demonstrated that panelists perceived demand-side challenges as being impediments to the growth of both production and consumption within the plant-based meat sector in Brazil. For example, among the actions for scaling PBM production, *protein sources* was identified as the most important action, *level playing field* was identified as being the most neglected, and *price* was identified as the most tractable priority action. Therefore, it appears that most panelists did not consider it likely that Brazil could develop a strong level of production of PBM without also dedicating resources to scaling PBM consumption within Brazil. Our findings demonstrate, perhaps unsurprisingly, that the panelists perceived production and consumption as being closely connected and interdependent. Somewhat analogously, Brazil is the world's largest beef exporter yet these exports account for only about 20% of all beef produced in Brazil, with the dominant domestic market accounting for the large majority (Zu Ermgassen et al., 2020).

4.4 Prioritization

The Importance, Neglect, and Tractability framework from the Effective Altruism movement offers a philosophy and a set of tools with which to consider the allocation of scarce resources and the prioritization of alternative actions (Todd, 2013). An Effective Altruism approach can help to guide resource allocation and could thus be of utility to stakeholders including investors, philanthropists, and funders. For example, our results could help guide philanthropic decision making by identifying important, neglected, and tractable actions that would benefit from strategic funding. Some actions, such as improving sensory profile, were identified as important and tractable for scaling consumption, but are not neglected and so may be less of a priority for funders (Figure 2). Our results could also help non-profit organizations such as the Good Food Institute and New Harvest, who advocate for alternative proteins and fund alternative protein related research, to determine where to focus their strategic endeavors and resources.

4.5 Methods: strengths and limitations

Our methodology had several strengths, which enabled us to garner expert opinion and draw interesting conclusions. First, the Delphi technique facilitated interaction between respondents, enabling a form of asynchronous dialogue that appears to have changed some panelists' minds between rounds. We found that there was greater consensus among panelists concerning the importance, neglect, and tractability rankings of most actions for promoting PBM production and consumption in Brazil in R2 than in R1. The only exception was that in R2 there was more disagreement concerning the relative importance of different production priority actions. Collectively, these findings suggest that the Delphi method was effective in facilitating interaction and dialogue between panelists. Second, our survey collected complementary quantitative and qualitative data, which enabled us to both identify priority actions and to explain some of the rationale panelists used in ranking the importance, neglect, and tractability of different actions. Third, the

method we employed in this research is a replicable way of assessing priorities. It could be applied in other geographies, with other alternative protein types and forms, and/or in relation to other emerging food technologies.

Our methodology was also subject to some caveats and limitations. First, expert opinion is generally depicted low on the evidence pyramid relative to other forms of data. That said, it is entirely appropriate for forecasting studies of an emergent technology (Feng et al., 2022) where few other forms of analysis are possible. Second, our panel was modest in size ($N = 9$) and while it had representation from several different sectors it was inevitably not perfectly balanced. The panel was too small to be able to conduct meaningful analyses that disaggregated the data according to panelist affiliations (e.g., responses from private sector vs. research panelists). Our recruitment process was constrained by our access to networks of qualified experts that could serve as panelists, and the willingness of panelists to participate in the somewhat time-intensive study. The optimal size for the Delphi method can be 10–15 (Hsu and Sandford, 2007); our final panel (following attrition) was one member smaller than this optimal range. Third, the first round of data collection lasted 4 weeks, and a further 10 days passed before we began the second round of data collection due to the time needed to process data gathered in the first round. The time lag between the two rounds of data collection could conceivably have affected how panelists thought about their responses in ways we were not able to account for in our study design. Finally, there was a limited response range in participants' action rankings (e.g., no action received a score below 50 by any panelist). This could indicate that panelists perceived all actions as being somewhat necessary, or they were hesitant to rank any action as a low priority. Previous research has found that PBM experts in Brazil tend to be generally optimistic about the future of PBM in Brazil as compared to PBM experts in Europe, perceiving a higher future consumer demand for PBM products with more optimistic outlooks about the business opportunities that the PBM sector could offer (Morais-da-Silva et al., 2022b).

Additionally, there was no clear systematic way to construct the initial list of possible actions. An alternative approach could have been to use the first round to openly solicit ideas from panelists, but this would have placed an onerous burden on respondents and would have had no greater guarantee of generating a comprehensive list. In our research, we asked panelists for suggestions of additional potential actions in the first round of data collection, but we elected not to include their suggested actions in the second round of data collection because (a) few novel actions were suggested (and none by more than one panelist), and (b) we would not have been able to employ the iterative Delphi technique for these responses. This could have been resolved by including a third round of the survey (and providing panelists with the responses to an expanded set of actions in the third round), but we were concerned about attrition because we sensed panelist fatigue even after the first round.

Finally, we chose to keep the scope and focus of the research relatively narrow to explore a single set of alternative protein products (i.e., plant-based meat). Soliciting expert opinion on more than one type of alternative protein product could have risked expert panel confusion or the potential for responses that conflated different considerations across alternative protein product types. In principle, one could conduct multiple parallel studies, with different panels discussing the same questions in response to different types and forms of alternative protein. However, doing so would require a much larger panel of experts to include representation of the combination of different sectors and different forms or types of alternative proteins. Conducting multiple parallel studies could also be unreasonably cumbersome for panelists with expertise that relates to multiple alternative proteins or could dilute the strength of expertise on any one panel.

4.6 Future research

Our findings indicate a clear need for identifying effective pathways to reduce the cost of plant-based meat to scale up both production and consumption. There may be multiple different ways in which retail prices may be reduced, including by investing in, supporting, or subsidizing one or more different stages of the supply chain. Research that identifies the most effective ways to reduce prices for consumers may have considerable potential to help scale up the PBM sector in Brazil. From a technological point of view, the alternative protein field is rapidly developing. Alternative protein technologies are increasingly used in combination with one another depending on the desired end product formulation (e.g., fermentation technologies are used to create ingredients for incorporation into PBM products). Research and development initiatives utilizing such breakthrough technologies could be directed toward making rapid advances in improving the sensory profile of PBM products to more closely mimic their animal-based analogs. Moreover, future research could also explore the impacts of innovation and diversification of products in the PBM sector, especially as it relates to actual consumer food choice behavior rather than stated intentions. Although hamburgers, meatballs, and sausages are frequently found in supermarkets, products like local meals, ready-made meals, and blended products mixed with cultivated meats could enrich the options available to consumers and potentially increase PBM sales. Moreover, studies could also address the roles that retailers can have in stimulating PBM product adoption and sales. Finally, future research could usefully explore how regulatory landscapes or consumer food cultures present in different geographies may affect expert assessment of which priorities are most needed for scaling the production and consumption of alternative protein products.

5 Conclusion

In this research, we employed the Delphi technique to assess expert opinion concerning the relative importance, neglect, and tractability of 14 actions to scale the production and consumption of plant-based meat (PBM) in Brazil. Our panel of nine experts collectively identified reducing product costs, championing the creation of a level regulatory playing field, and identifying new crops as viable sources of plant protein as the top priority actions to scaling PBM production in Brazil. Similarly, they identified reducing product costs, improving the sensory experience of products, and championing the creation of a level regulatory playing field as the top priority actions to scaling PBM consumption in Brazil. The highest degree of consensus among panelists was that reducing the price of PBM was

the most important action to scale up consumption. With respect to production, different actions emerged as the most important (*protein sources*), neglected (*level playing field*), and tractable (*price*). Similarly, with respect to consumption, *price* was the action identified as being most important, *level playing field* was the action identified as being most neglected, and *sensory profile* was the action identified as being most tractable. Panelists evaluated *start-up support*, *manufacturing efficiency*, and *manufacturing facility capacity* as the lowest priority actions.

The findings from this research could be usefully leveraged to guide the decision-making processes of stakeholders interested in supporting the growth of Brazil's PBM sector, to determine where to focus their attention and energy. Most obviously, our research suggests a need to prioritize reducing the price of PBM for consumers, as well as creating a more equitable regulatory environment, and supporting the search for new crops for PBM production. Our findings align with previous studies that have revealed that Brazilian consumers tend to correctly perceive PBM products to be more expensive (on average) than animal products (e.g., Reis et al., 2023). Further research is needed to determine whether PBM price reductions actually affect food choice behavior and lead Brazilian consumers to purchase PBM as a substitute for animal meat. Private sector companies, governmental agencies, and non-profit organizations likely each have different tools available to them to support the pursuit of these goals, directly or indirectly.

Our research extends the literature on alternative proteins in three ways. First, our study engages with the reality that decision-makers (e.g., funders) have finite resources to invest in the scaling up of alternative proteins. It focuses not on *characterizing* the various technological, policy, and market barriers but on *prioritizing* the potential actions that decision-makers could take in the hope of informing a more strategic and efficient approach to overcoming the most pressing barriers to scaling up PBM. Second, our study adopts an established framework to differentiate 'priority' in the context of scaling up PBM into three distinct traits (importance, neglect, and tractability), which more clearly identifies whether and why any given action should be a priority for decision-makers. Third, our study is methodologically novel in this topic area. Our use of the Delphi technique was successful in facilitating panelist dialogue between rounds of data collection, suggesting that the methodology used could be applied in other geographies, to evaluate other alternative protein types and forms, and/or in relation to other emerging food technologies.

Data availability statement

The quantitative datasets generated for this study and the code used to analyze these data are included in the Supplementary Material of this paper.

Ethics statement

The studies involving humans were approved by University of Colorado Boulder Institutional Review Board (Protocol: 21-0543). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

PN: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. WE: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. MH: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. RM-d-S: Investigation, Methodology, Writing – review & editing. MSH: Writing – review & editing. AH: Writing – review & editing. GR: Writing – review & editing.

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Conflict of interest

AH was employed by the Brazilian Agricultural Research Corporation (Embrapa).

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.

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

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1303448/full#supplementary-material

SUPPLEMENTARY TABLE S1
Aggregated quantitative results from two rounds of an online survey using the Delphi method to assess expert opinion of the relative importance, neglect, and tractability of 14 possible priority actions to scale up the production and consumption of plant-based meat in Brazil. Scores represent the mean ± standard deviation across the panel of nine experts for round one (R1) and round two (R2).

SUPPLEMENTARY TABLE S2
Aggregated quantitative results from two rounds of an online survey using the Delphi method to assess expert opinion of the relative importance, neglect, and tractability of 14 possible priority actions to scale up the production and consumption of plant-based meat in Brazil. Scores represent the median value across the panel of nine experts for round one (R1) and round two (R2).

SUPPLEMENTARY TABLE S3
Aggregated quantitative results from two rounds of an online survey using the Delphi method to assess expert opinion of the relative importance, neglect, and tractability of 14 possible priority actions to scale up the production and consumption of plant-based meat in Brazil. Values represent the change in standard deviation between round one (R1) and round two (R2), as a measure of the change in consensus among panelists. A negative value indicates less agreement (red) in the second round (R1_sd-R2_sd < 0; R2_sd >R1_sd). A positive value indicates more agreement (green) in the second round (R1_sd-R2_sd >0; R2_sd < R1_sd).

SUPPLEMENTARY TABLE S4
Aggregated quantitative results from two rounds of an online survey using the Delphi method to assess expert opinion of the relative importance, neglect, and tractability of 14 possible priority actions to scale up the production and consumption of plant-based meat in Brazil. Values represent those actions deemed to be of greatest priority by the expert panel, derived by averaging the importance, neglect, and tractability scores, separately for round one (R1) and round two (R2).

SUPPLEMENTARY NOTE S1
The search terms used to identify relevant literature.

SUPPLEMENTARY NOTE S2
The Qualtrics survey used in round one (R1) to determine the expert opinion of panelists on the relative priority of 14 potential priority actions to scale up the production and/or consumption of plant-based meat in Brazil.

SUPPLEMENTARY NOTE S3
The Qualtrics survey used for R2 to determine if the opinion of panelists changed after reading the opinions of other experts from R1.

SUPPLEMENTARY DATA S1
Anonymized quantitative data from round one (R1) of an online survey using the Delphi method to assess expert opinion of the relative importance, neglect, and tractability of 14 possible priority actions to scale up the production and consumption of plant-based meat in Brazil.

SUPPLEMENTARY DATA S2
Anonymized quantitative data from round two (R2) of an online survey using the Delphi method to assess expert opinion of the relative importance, neglect, and tractability of 14 possible priority actions to scale up the production and consumption of plant-based meat in Brazil.

SUPPLEMENTARY DATA S3
R code to replicate the figures and tables from this paper, using Data S1 and Data S2.

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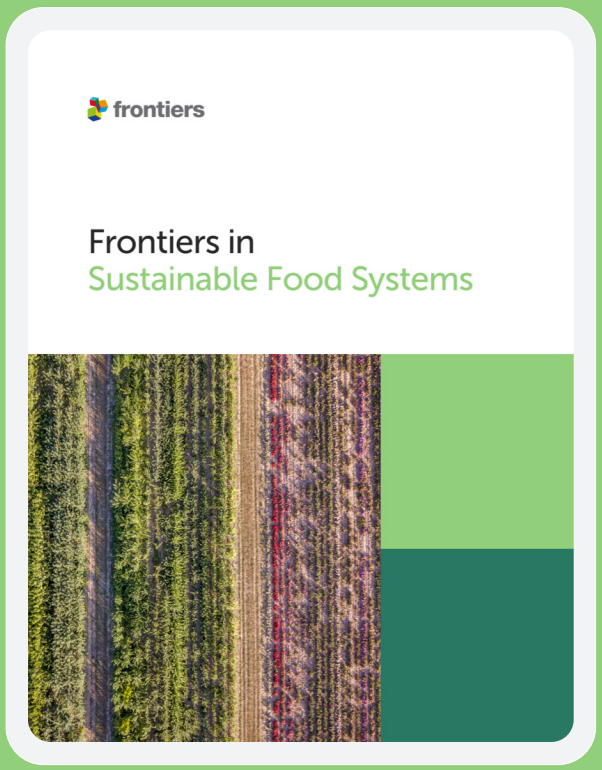

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