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Review: Trends for meat, milk and egg consumption for the next decades and the role played by livestock systems in the global production of proteins

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Meeting the food demands of a growing global population within planetary boundaries is a challenge. Sustainably producing animal-sourced foods while supplying sufficient protein to meet the requirements of a healthy diet is a particular challenge. This paper informs the development of pathways to sustainable animal production by examining trends in animal-sourced foods since 2000, including the significance of animal- relative to plant-protein sources. Drawing on three distinct scenarios defined by the Food and Agriculture Organization (**FAO**), (i.e. Business As Usual (**BAU**), a continuation of historical trends of food preferences including initiatives to address Sustainable Development Goal targets; Stratified Societies (**SSs**), leaving challenges unattended; and Towards Sustainability (**TS**); a more equitable global society and more sustainable food system due to effective polices), future demand for animal-sourced foods is projected. Analysis is based on FAO Food Balance Sheet data (2000–2017) and projected national protein demand per capita (2012–2050). Analysis is disaggregated to five global regions defined by the World Health Organization. It finds that patterns of past demand for animal-sourced foods vary by food (e.g. red vs white meat) and region. However, the European region consistently has the highest levels of consumption of animal-sourced foods, while the South-East Asian and African regions have the lowest. The ratio of animal to plant-sourced protein varies across regions, ranging from 0.29 in Africa to 1.08 in Europe in 2017. Over time, the ratio is relatively stable or moderately increasing, driven by rising incomes in low- or middle-income countries. Under the future scenarios, all World Health Organization regions show a marked increase in demand for animal-sourced protein across BAU and SS. The TS scenario, however, projects notable declines in consumption across Europe and the Americas when compared to the 2012 BAU baseline, with a decline in milk also in the Western Pacific. In contrast, meat and milk consumption in Africa and South-East Asia is projected to increase, reflecting their far lower starting consumption levels. The analysis and subsequent discussion highlight the importance of having regional-specific strategies to deal with the challenge of sustainable livestock production and consumption, with a requirement to consider the impact of actions in one region on others. Clearly, the challenge is not merely one for science and technology but one based on wider aspects of the food system and its diverse stakeholders.

Implications

Without changes to the food system, projected global animal-sourced protein demand cannot be sustainably satisfied. The findings of the paper have significant implications for those involved in animal-based food supply chains, and policy makers seeking to influence the practices in such chains. It underlines aspects to be considered when redesigning such chains to address environmental, economic and social concerns, including those relating to nutrition, health and equity. The need to develop pathways that are context-specific, with consideration given to the food source and the region, is also emphasised. Finally, it highlights the trade-offs involved in seeking to address such challenges.

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Introduction

The global population is predicted to grow to 9.7 billion by 2050, representing an increase of about one-third compared to 2015 (Food and Agricultural Organization (FAO), 2018a). This represents a challenge of not just providing more food for a growing population, but to do so taking health inequalities such as malnutrition and obesity into account. The importance of this is clearly demonstrated by the fact that globally there are approximately two billion overweight or obese adults and almost one billion undernourished people (Intergovernmental Panel on Climate Change (IPCC), 2019), with high rates of these forms of malnutrition coexisting in many countries (FAO, 2018a). Furthermore, ongoing challenges to the food system, including increasing greenhouse gas (**GHG**) emissions, loss of natural ecosystems and declining biodiversity resulting from an expansion of land and fresh water used to produce food for a growing population (IPCC, 2019), lead to a recognition that current patterns of food production and consumption are not sustainable (Steenson and Buttriss, 2020). Food security concerns, brought into sharp focus by the Covid19 pandemic (Swinnen and McDermott, 2020), add to calls to change the food system (FAO, 2018a; Willett et al., 2019). The EAT-Lancet Commission (Willett et al., 2019) concluded that 'widespread multisector, multilevel action is needed including: a substantial global shift towards healthy dietary patterns; large reductions in food loss and waste; and major improvements in food production practices'.

A global diet for health and sustainability, to feed the increasing population within the current planetary boundaries, was recommended by the EAT-Lancet report in 2019 (Willett et al., 2019). This report called for an increase in consumption of plant-based foods and a decrease in animal-sourced foods. Similarly, regional food policies, e.g., the recent European Union Farm to Fork strategy (European Commission, 2020), have begun to promote an increase in plant-based foods. Indeed, this trend has also been observed in food based dietary guidelines, with some countries (albeit less than 10 out of a possible 90) recommending a decrease in animal-sourced foods to achieve health and sustainability targets (Herforth et al., 2019). However, decreasing animal-sourced foods (meat, dairy and eggs) may result in a diminished protein intake in terms of both protein quality and quantity (Steenson and Buttriss, 2020), and concerns may also arise in relation to some micronutrients (e.g. iron, zinc, vitamin B12 and fatty acids) if these are replaced with plant-based foods (Leroy and Cofnas, 2020). Achieving recommended intakes of protein is essential to maintain healthy muscle mass as well as to prevent ill health amongst vulnerable groups, such as sacropenia in older adults. Hence, it is important to examine current and projected intakes of both animal foods and animal derived protein to address the quality as well as quantity of food produced to feed the growing global population. Indeed many governments around the world, from Germany to Manitoba, have developed, or are developing, holistic sustainable protein plans to support their climate objectives, and ensure the long-term viability of their domestic agriculture and food and drink industries (Clark and Lenaghan, 2020).

Animal-sourced foods are reported to be the most resource-intensive, with some researchers drawing the conclusion that they are 'hence [the] most environmentally damaging of all food types to be produced' (Tucker, 2014). Animal-sourced foods are also criticised for their contribution to anti-microbial resistance, non-communicable diseases in humans, their potential to be a source of zoonotic disease, as well as their impact on animal health and welfare (Baltenweck et al., 2020). Furthermore, as stated by Baltenweck et al. (2020), 'Public debates over the economic, health, social, and environmental merits of livestock are growing increasingly acrimonious'. Other authors however argue that there are two sides to this narrative with animal-based foods providing many health and environmental benefits as well as ecosystem services (Henchion et al., 2017; Hyland et al., 2017a and 2017b; Tarawali, 2019; Leroy and Cofnas, 2020; Henchion and Zimmermann, 2021). They also argue that there are negative environmental and health issues associated with plant-based foods (Henchion et al., 2017) (e.g. plant-based proteins may not contain all essential amino acids and may contain some anti-nutritional compounds (Henchion et al., 2017)). Regardless of the balance of the argument, while a growing population will result in an increased demand for food, other trends relating to economic development mean that the growth in demand for different foods is not uniform. In particular, low levels of animal-sourced foods are associated with low-income countries with expectations of demand for such foods to increase as incomes increase. With global (COP 21: United Nations Framework on Climate Change Paris Agreement) and regional commitments (European Union Farm to Fork strategy (European Commission, 2020)) to reduce GHG, improve water quality and biodiversity, address antimicrobial resistance, and to improve diets and health, there is a significant challenge facing the livestock sector to be part of the solution rather than part of the problem.

To inform such discussions in future, this paper examines trends in animal-based food consumption in different regions of the world since 2000. In addition, the ratio of animal- to plant-sourced protein is examined to take a wider dietary perspective into account. Looking forward, it draws on three distinct scenarios identified by the FAO (FAO, 2018a) that boldly, partially or not at all, deal with the key challenges to food security, nutrition and sustainability up to 2050, to predict future demand for animal-based foods in the different scenarios. It concludes by discussing possible strategies in the evolution of such patterns by considering the factors that may lead to improvements in the sustainability of animal-based foods and/or moderate demand.

Methodology

Food and protein supply data from 2000 to 2017 were accessed from the FAOSTAT portal (FAO, 2020a and 2020b). Specifically, the Food Balance Sheets (**FBSs**) which contain information on total and per capita food supplies, disaggregated into specific food components, were obtained. While balance sheets data have limitations, as they do not consider materials such as bones, fat and other materials that are discarded prior to consumption, and thus may overestimate per capita consumption, these data have been widely used to guide agricultural and food policy due to their availability on a global basis and over significant time periods. Therefore, they are appropriate to enable comparisons between regions over time.

Data for three specific food groups were extracted from the FBS datasets:

(a) Meats, which were disaggregated into red meat (bovine meat, mutton and goat meat) and white meat (pig meat and poultry meat). Data for 'Other meats' which comprise birds, horses, donkeys and mules, camels and other camelids meat, rabbit, rodents, game, land snails, and other processed meats not listed elsewhere were not extracted. (While it is acknowledged the pig meat is often considered a red meat due to its haemoglobin content, it is usually considered a white meat from a gastronomic perspective. Furthermore, the classification used here reflects differences in the digestive systems of ruminants and monogastrics, and consequently differences in production systems and associated sustainability challenges);

(b) Dairy, which consists of milk, butter and ghee, and cream;
(c) Eggs.

For each of these categories, the total per capita food supply and the per capita protein supply were extracted. These items are reported in different units (food supply in kg/capita per year; protein supply in g/capita per day). Protein supply was adjusted to match the total food supply unit following Eq. (1),

$$protein_{adj} = \begin{cases} protein * \frac{365}{1000} normal\ \ year \\ protein * \frac{366}{1000} leap\ \ year \end{cases} \quad (1)$$

where $protein_{adj}$ is the adjusted protein consumption in kg/capita per year, and *protein* is the consumption as reported by the FAO in g/capita per day.

The acquired data were then summarised for five global regions, based on the World Health Organization (**WHO**) regions as defined in Annex 3 of the 2020 World Health Statistics (WHO, 2020). As not all countries included in the WHO regions had FAO food supply data recorded, our analysis does not include all countries in the WHO regions. The countries in each region included in our analysis are listed in Table 1.

To analyse past trends in animal and plant-based protein, FAO data were again used. The study obtained FAO FBS data from 2000 to 2013, the latter being the last available year in the old FBS dataset (FAO, 2020a), and the new FBS from 2014 to 2017 (FAO, 2020b). The FBSs were downloaded as two comma separated value (.csv) files from the FAOSTAT database; one the old FBS from 2000 to 2013 and another the new FBS from 2014 to 2017. Thereafter, the two databases were merged into a single database from 2000 to 2017 for protein supply (g/capita per day).

For analysis of future projections, data were obtained from the FAOSTAT portal where the FAO has projected national protein demand per capita to 2050 (FAO, 2018b). The same method was adopted as previously outlined, where projected protein supply data were downloaded from the FAO database in .csv format (FAO, 2018b). Projections of protein supply (g/capita/day) from 2012 to 2050 were aggregated to reflect WHO regional constitutes as per Table 1. Food groups ‘Poultry meat’, ‘Pig meat’, ‘Sheep and goat meat’, ‘Beef and veal’ and ‘Raw milk’ were extracted from the dataset. There was no food group dedicated to eggs. Red meat was calculated as ‘Beef and veal’ plus ‘Sheep and goat meat’ while white meat comprised ‘Pig meat’ plus ‘Poultry meat’.

The projections were based on three defined trajectories that represent alternative future food systems from the FAO report *Food and Agriculture Projections to 2050* (FAO, 2018a). Such scenarios were identified by the FAO based on providing prominence to historical trends while denoting the manner in which key challenges to food security, nutrition and sustainability are considered: i.e. strongly, partially or not at all. The first scenario, Business as Usual (**BAU**), assumes a continuation of historical trends of food preferences. In this projection, efforts are made to achieve and maintain Sustainable Development Goal (**SDG**) targets but these efforts ultimately fail to address many of the issues facing food and agriculture. The second scenario, the Stratified Societies (**SS**) pathway, places emphasis on the effects of ignoring the current and future challenges facing food and agricultural systems and thereby leaving them unattended. The third scenario, Towards Sustainability (**TS**), forecasts a more equitable global society whereby several SDG targets are almost universally achieved and food systems move towards sustainability due to the adoption of effective policies. Consequently, agricultural GHG emissions are dramatically reduced and climate change is mitigated. All scenarios use the same population projections where growth is high in Asia (until 2050) and Africa, and low elsewhere. Please refer to Supplementary Material (Table S1) for more detail on the assumptions used to project each pathway.

Global trends in food consumption

The results of the analysis start with a presentation on consumption of the different animal foods according to five global regions. Figs. 1–4 show demand for red meat, white meat, dairy, and eggs across the regions from 2000. (It should be noted that, except for EURO, there was a significant downward trend in consumption between 2013 and 2014. This is the result of a change in FAO recording methodology. The main driver of the drop-off is likely a change in population figures used to calculate the per capita supplies (FAO, 2020c). Hence, observation of trends over time need to be considered with care). With regard to red meat, Fig. 1 shows that patterns of consumption across regions are not homogenous, with relatively modest movement over time in some regions but more dramatic variations in others (EMRO, WPRO). Nonetheless, consumption now is less than it was in 2000 in all cases except SEARO. Fig. 2 shows that white meat consumption exhibits a different pattern with upward trajectories in all regions.

Table 1
The Five World Health Organization Regions and the countries included in each region. Source: WHO (2020).

Region	Abbreviation	List of countries
African Region	AFRO	Algeria, Angola, Benin, Botswana, Burkina Faso, Cabo Verde, Cameroon, Central African Republic, Chad, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, South Africa, South Sudan, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
Region of the Americas	PAHO	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bolivia (Plurinational State of), Brazil, Canada, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, the United States of America, Uruguay, Venezuela (Bolivarian Rep. of)
South-East Asia Region	SEARO	Bangladesh, Democratic People's Republic of Korea, India, Indonesia, Maldives, Myanmar, Nepal, Sri Lanka, Thailand, Timor-Leste.
European Region	EURO	Albania, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Tajikistan, Turkey, Turkmenistan, Ukraine, United Kingdom of Great Britain & Northern Ireland, Uzbekistan
Eastern Mediterranean Region	EMRO	Afghanistan, Djibouti, Egypt, Iran, Iraq, Jordan, Kuwait, Lebanon, Morocco, Oman, Pakistan, Saudi Arabia, Sudan, Tunisia, United Arab Emirates, Yemen.
Western Pacific Region	WPRO	Australia, Brunei Darussalam, Cambodia, China, Fiji, Japan, Kiribati, Lao People's Democratic Republic, Malaysia, Micronesia (Federated States of), Mongolia, New Zealand, Philippines, Republic of Korea, Samoa, Solomon Islands, Vanuatu, Vietnam

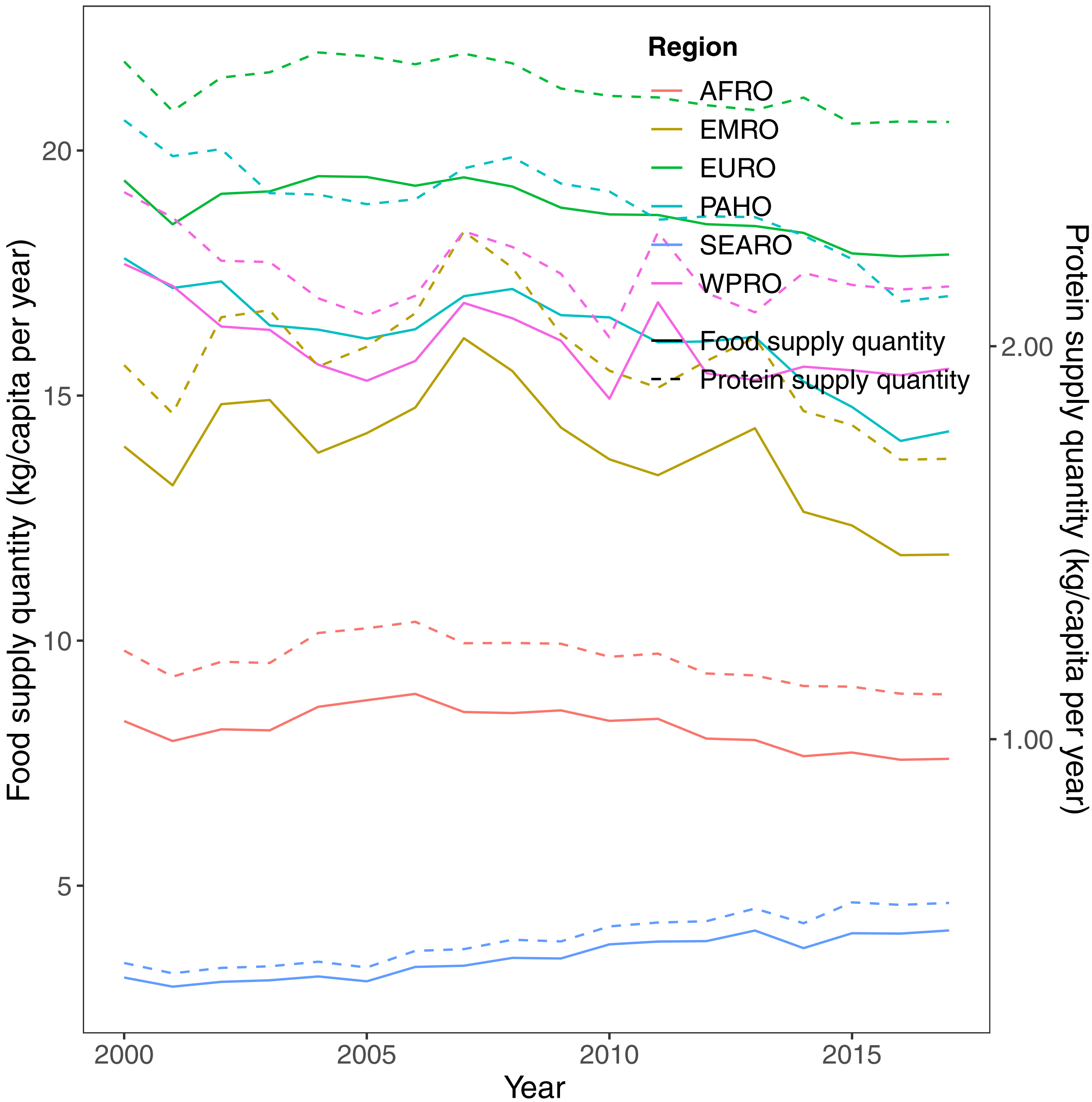

Fig. 1. Total food and protein supply quantities in kg/capita per year of red meat (bovine meat, and mutton and goat meat) from 2000 to 2017 for five global regions (defined in Table 1).

It also shows significant differences in levels of consumption across regions from 10.3 kg/capita per year in AFRO in 2017 to 48.8 kg/-capita per year in EURO in the same year. This is a higher range than is the case for red meat where the highest level of consumption was 17.9 kg/capita per year in EURO and the lowest level of consumption was 4.1 kg/capita per year in SEARO in the same year. The pattern of dairy consumption (Fig. 3) contrasts with both meats, being more stable over time across all regions. The range in the level of consumption across regions is very pronounced in relation to dairy, from 56.5 kg/capita per year to 443.5 kg/capita per year in SEARO and EURO, respectively. While there is a more limited range in relation to eggs (Fig. 4), EURO continues to have the highest level of consumption (at 10.6 kg/capita per year) while AFRO has the lowest (1.7 kg/capita per year). There is a general upward trend, with EMRO and AFRO more stable over time.

Table 2 presents a summary of the change in consumption of animal foods across the regions between 2000 and 2017, from those with the highest level of consumption to those with the lowest levels of consumption. European region has the highest level of consumption of all animal-based foods while AFRO has the lowest level of consumption of red meat and dairy in both years. SEARO has the lowest level of consumption of white meat and eggs in both periods. There is very little change in the relative ordering except for a swapping of the relative order between PAHO and WPRO for second and third positions with respect to red meat and eggs. Thus, overall it shows, despite changes in levels of consumption,

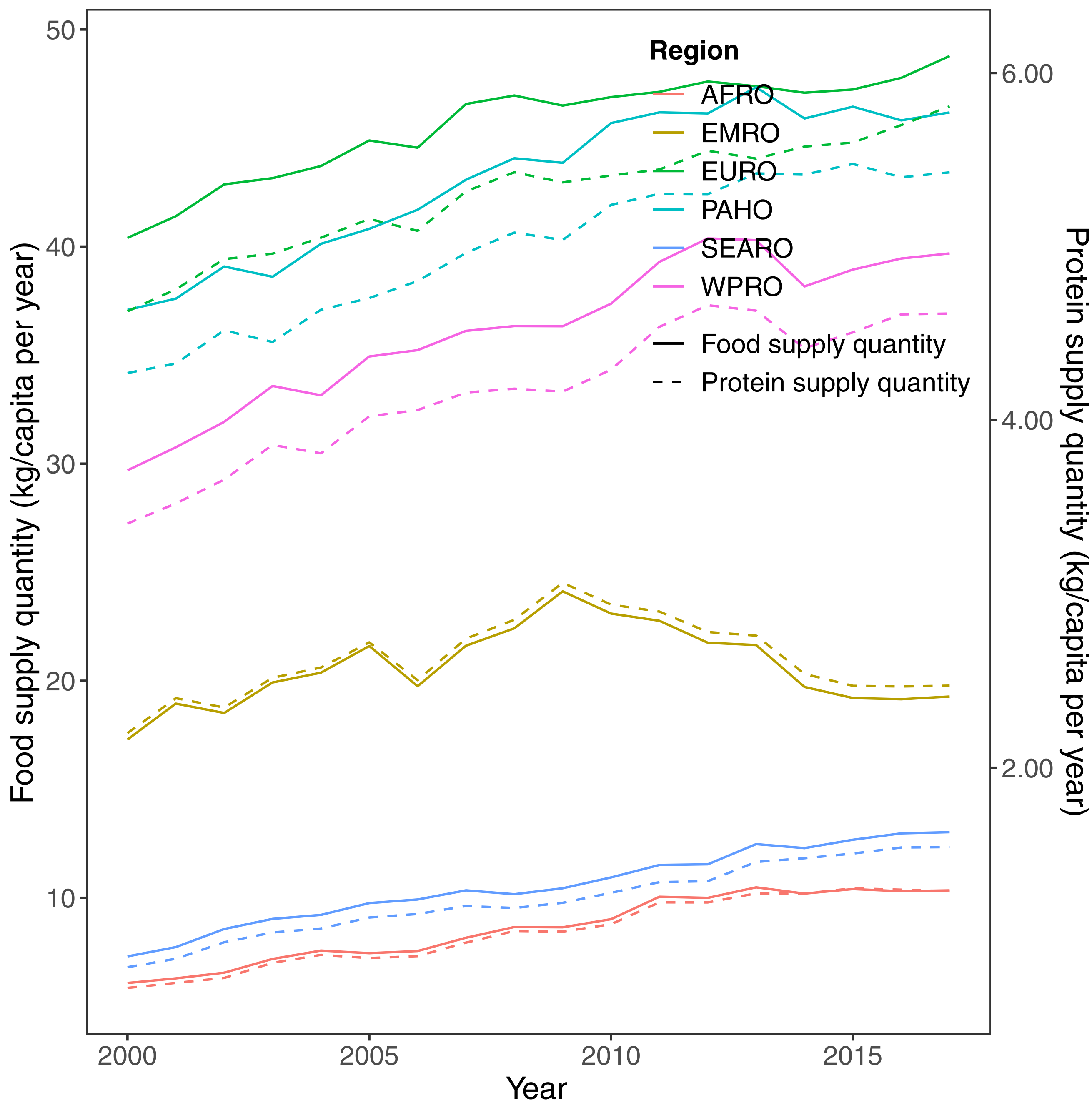

Fig. 2. Total food and protein supply quantities in kg/capita per year of white meat (poultry and pig meat) from 2000 to 2017 for five global regions (defined in Table 1).

the relative demand of different animal-sourced foods has not changed very much regionally or over time.

Table 3 shows the contribution of animal-sourced foods to protein consumption as a ratio relative to vegetal-based foods. It shows that in general the protein of plant origin is significantly more important than that of animal origin, except in EURO, where the ratio is above 1 since 2002. Furthermore, it is clear that, despite widespread criticism of animal-based foods, their contribution to the diet is broadly either increasing or stable (EMRO is a slight exception as the ratio declined from 0.45 to 0.43 between 2000 and 2017). The differential rates of change are also evident with SEARO showing the strongest upward trajectory over time, with the ratio increasing from 0.21 to 0.29 between 2000 and 2017. Fig. 5 shows the change in sources of protein supply over the period. On a regional basis, it shows the highest percentage changes in SEARO for all food groups examined, with the exception of vegetal where AFRO is one percentage point ahead in terms of change. On a food basis, eggs show significant change, particularly in SEARO, PAHO and WPRO. It should be noted that there is heterogeneity within each of the regions discussed due to the large geographical spread of each.

Table 4 illustrates regional projections of animal-sourced protein supply (g/capita per day) from 2012 to 2050 across the three distinct scenarios defined by FAO (2018b) as outlined in the methodology. (Table S2 presents an expanded version of Table 4 as it details projections according to individual meat food groups). Each scenario has a distinct effect on per capita future protein demand, which is dependent on the assumptions made. For

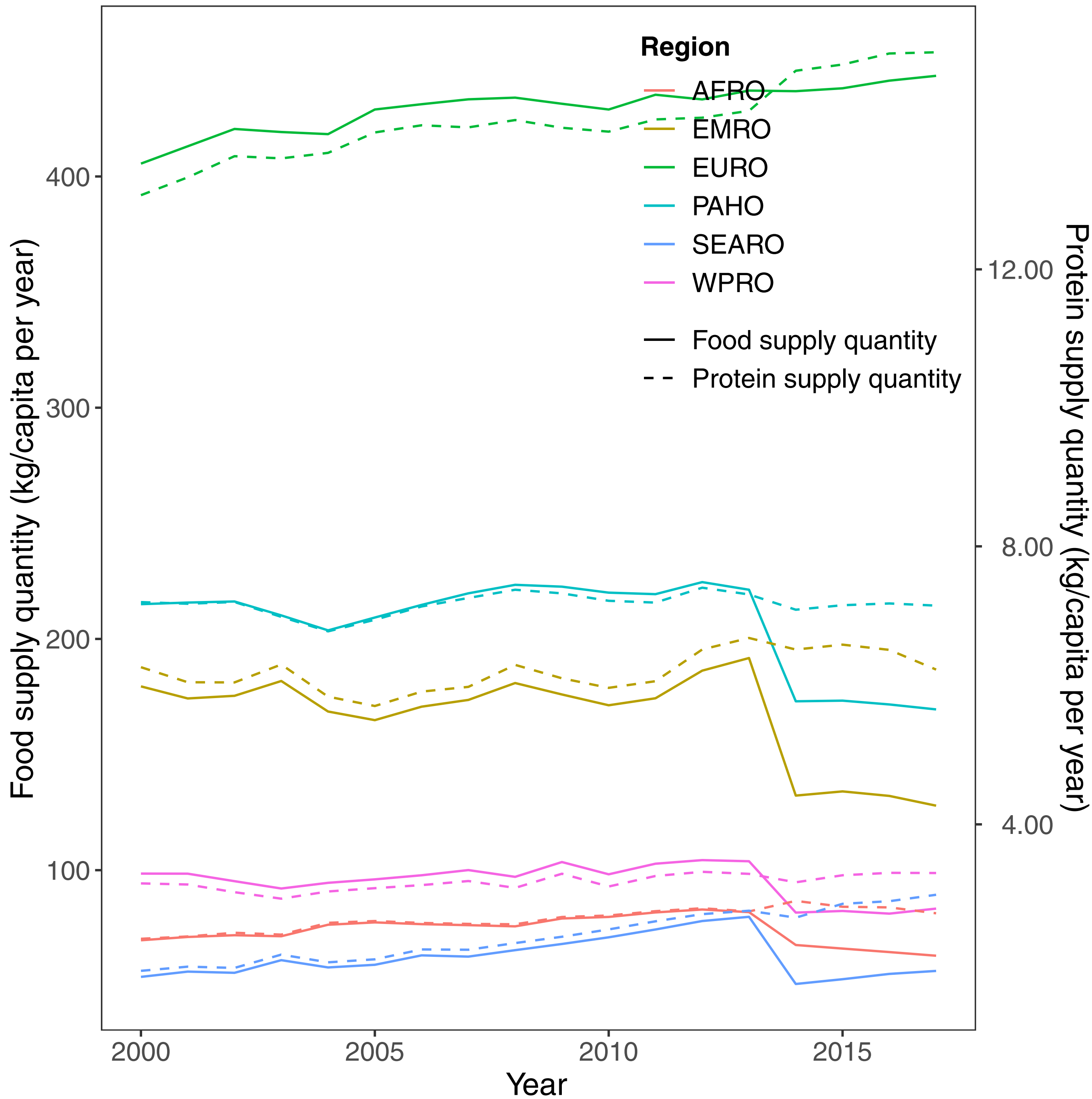

Fig. 3. Total food and protein supply quantities in kg/capita per year of dairy (milk, butter and ghee, and cream) from 2000 to 2017 for five global regions (defined in Table 1).

instance, in a BAU scenario, it is expected that rising incomes in high-income countries will lead to lower consumption of animal-based food, giving way to increased fruit and vegetable intake. However, this effect is less pronounced when observed at a regional level, as the effect is diluted by a greater number of lower income countries within the region (Table 4). The pathway predicts that lower income countries start adopting patterns similar to their higher income counterparts after the second half of the projection period. In the SS projection, preferences for animal products remain high in high and lower income countries due to increased incomes but, also, as a result of populations that are less likely to be educated on the nutritional and environmental consequences of dietary preferences. Similar to BAU, the TS scenario assumes that highly informed consumers consume lower levels of animal-based foods; such informed consumers are expected to be especially prevalent in higher income countries.

All WHO regions show a marked increase in demand for animal-sourced protein across the BAU and SS projections in each of the years documented. The SS pathway signifies large increases in consumption across all regions. The TS scenario however depicts notable percentage declines in consumption levels across EURO and PAHO when compared to the 2012 BAU baseline, with a decline in milk also in WPRO. In contrast, AFRO and SEARO in particular are projected to increase meat and milk consumption, reflecting their far lower initial consumption levels. Pig meat in EURO and sheep and goat meat in PAHO face the largest decreases, with a 15.6% and 12.7% reduction respectively in the TS scenario (Table S2). Indeed, in the TS scenario, EURO and PAHO are the only

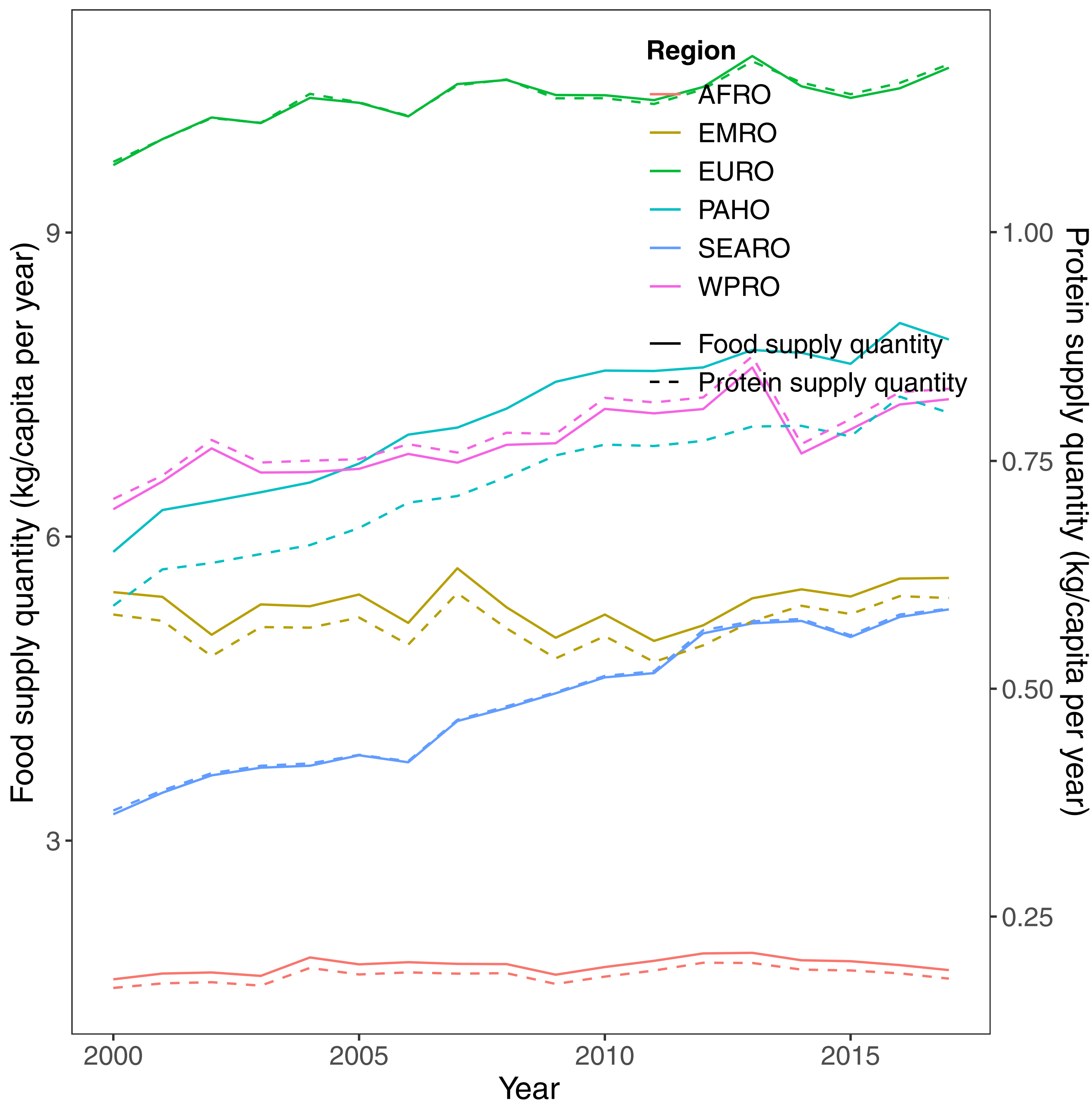

Fig. 4. Total food and protein supply quantities in kg/capita per year of eggs from 2000 to 2017 for five global regions (defined in Table 1).

Table 2
League table of consumption of animal foods[1] by region (defined in Table 1) in 2000 and 2017 (highest to lowest).

	Red meat		White meat		Dairy		Eggs	
Rank	2000	2017	2000	2017	2000	2017	2000	2017
1st	EURO	EURO	EURO	EURO	EURO	EURO	EURO	EURO
2nd	PAHO	WPRO	PAHO	PAHO	PAHO	PAHO	WPRO	PAHO
3rd	WPRO	PAHO	WPRO	WPRO	EMRO	EMRO	PAHO	WPRO
4th	EMOR	EMRO	EMRO	EMRO	WPRO	WPRO	EMRO	EMRO
5th	AFRO	AFRO	SEARO	SEARO	AFRO	AFRO	SEARO	SEARO
6th	SEARO	SEARO	AFRO	AFRO	SEARO	SEARO	AFRO	AFRO

[1] Red meat: bovine meat, mutton and goat meat; White meat: pig meat and poultry meat; Dairy: milk, butter and ghee, and cream; Eggs: Eggs.

Table 3
Regional evolution of protein consumption per capita (g/capita/day) from 2000 to 2017 expressed as the ratio of animal protein compared to vegetal protein. The percentage change of the 2000 animal to vegetal ratio to that of 2017 is also presented. Regions defined in Table 1.

Items	Region					
	AFRO	PAHO	SEARO	EURO	EMRO	WPRO
Protein consumption per capita (g/capita/day)						
Year						
2000	0.27	0.88	0.21	0.99	0.45	0.61
2001	0.26	0.87	0.22	1.00	0.44	0.62
2002	0.27	0.89	0.23	1.02	0.45	0.61
2003	0.27	0.86	0.24	1.02	0.46	0.62
2004	0.29	0.87	0.23	1.02	0.45	0.61
2005	0.28	0.87	0.23	1.05	0.45	0.62
2006	0.28	0.89	0.24	1.04	0.45	0.63
2007	0.28	0.90	0.24	1.06	0.47	0.65
2008	0.28	0.92	0.25	1.06	0.48	0.65
2009	0.27	0.91	0.25	1.04	0.47	0.64
2010	0.27	0.91	0.26	1.05	0.45	0.63
2011	0.28	0.91	0.27	1.05	0.44	0.66
2012	0.28	0.91	0.27	1.06	0.46	0.66
2013	0.28	0.90	0.28	1.05	0.47	0.65
2014	0.30	0.90	0.27	1.06	0.44	0.63
2015	0.30	0.90	0.28	1.06	0.44	0.64
2016	0.29	0.88	0.29	1.06	0.44	0.64
2017	0.29	0.88	0.29	1.08	0.43	0.64
% Change	6.88	−0.58	37.11	9.43	−3.03	4.52

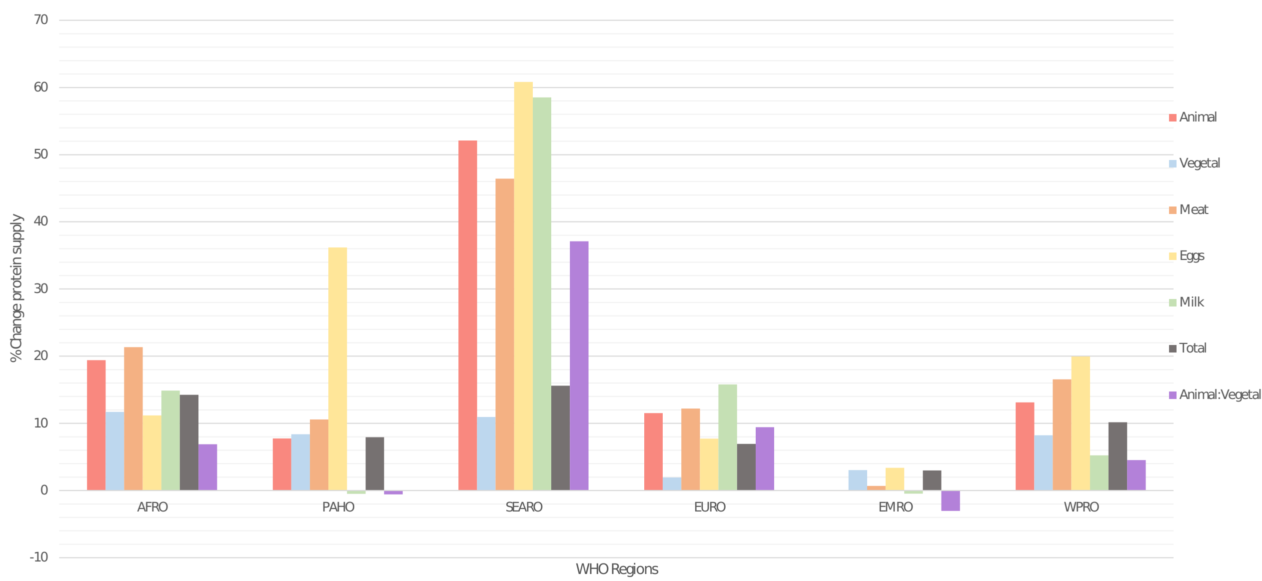

Fig. 5. Regional percentage change in protein consumption (g/capita per day) from 2000 to 2017 across different food groups (regions defined in Table 1).

regions in which meat consumption is reduced across all the meat types assessed. In contrast, AFRO, SEARO, EMRO (except sheep and goat) and WPRO are all predicted to have varying increases in demand across all categories (Table S2).

From a global (all regions) perspective, an increase in consumption in total animal-sourced protein is predicted in 2050 across all three scenarios when compared to the BAU 2012 baseline (Table 4). The BAU 2050 pathway involves a 17% increase whereas the SS projection predicts a 20.9% global rise in animal protein intake per capita. In comparison, the TS scenario forecasts relatively minor growth of 3% in consumption. In the TS pathway, it is primarily in AFRO and SEARO where nearly all of the growth in the scenario occurs. Evidently, increases as high as 50.8% and 56% are predicted for red meat protein consumption in AFRO and SEARO, respectively.

Discussion

As shown above, the demand for animal-sourced food products has increased over the past decade despite concerns about the environmental dimensions of their production. Moreover, the ratio of protein from animal and plant-sourced foods has remained relatively stable or has increased in favour of animal sources, despite the negative narrative around its impact on human health. However, if this level of per capita consumption is maintained to 2050, the global average demand for total animal-sourced food products will increase from 1.4 billion tonnes to 2.0 billion tonnes, approximately. Moreover, the expected increase in per capita demand, particularly in the currently less developed regions (Adesogan et al., 2020), will result in even higher levels of demand. As it is generally accepted that the current level of production is

Table 4
Regional projections of Animal Foods[1] protein supply (g/capita/day) to 2050 based on three different FAO scenarios[2]. Also presented is the forecasted percentage change in protein supply comparing 2012 BAU with each of the 2050 scenario projections. Regions defined in Table 1. Scenarios defined in Supplementary Table S2.

Region	2012			2030			2040			2050			2012 BAU vs 2050		
	BAU	SS	TS	BAU	SS	TS	BAU	SS	TS	BAU	SS	TS	BAU	SS	TS
AFRO															
Protein supply quantity (g/capita/day)															
White Meat (total)	3.3	3.3	3.3	4.0	4.6	4.1	4.4	4.6	4.5	4.9	4.5	5.0	48.3%	38.5%	51.7%
Red Meat (total)	3.4	3.4	3.4	4.2	4.7	4.5	4.7	4.7	4.9	5.1	4.6	5.2	49.3%	32.8%	50.8%
Milk	3.8	3.8	3.8	4.3	4.4	4.3	4.3	3.3	4.3	4.3	4.4	4.2	14.3%	15.8%	11.2%
PAHO															
Protein supply quantity (g/capita/day)															
White Meat (total)	14.2	14.2	14.0	15.8	17.3	13.9	16.3	17.4	13.9	16.7	17.2	13.9	17.3%	21.3%	−2.2%
Red Meat (total)	8.5	8.5	8.1	9.4	9.9	8.2	9.5	9.9	8.1	9.5	9.8	7.9	12.0%	15.3%	−6.6%
Milk	11.5	11.5	11.4	12.3	12.6	11.6	12.3	9.5	11.6	12.2	12.5	11.5	6.4%	8.3%	0.3%
SEARO															
Protein supply quantity (g/capita/day)															
White Meat (total)	3.6	3.6	3.6	5.0	5.8	4.7	5.2	5.8	5.1	5.5	5.5	5.5	52.3%	53.1%	50.6%
Red Meat (total)	1.2	1.3	1.3	1.8	2.0	1.7	1.9	2.0	1.8	1.9	1.9	1.9	56.1%	56.6%	56.0%
Milk	3.4	3.4	3.4	3.9	4.0	4.0	3.9	1.5	3.9	3.9	3.8	3.8	15.2%	13.7%	12.9%
EURO															
Protein supply quantity (g/capita/day)															
White Meat (total)	14.8	14.8	14.8	16.2	18.0	13.5	16.7	18.3	13.1	17.1	18.4	12.9	15.5%	24.2%	−13.0%
Red Meat (total)	6.9	6.9	6.9	7.7	8.4	6.8	7.8	8.3	6.6	7.8	8.3	6.4	13.5%	20.2%	−6.9%
Milk	19.3	19.3	19.3	19.9	20.2	18.8	19.9	6.9	18.5	19.8	20.4	18.5	2.4%	5.4%	−4.5%
EMRO															
Protein supply quantity (g/capita/day)															
White Meat (total)	6.9	6.9	6.9	8.2	9.3	7.1	8.7	9.5	7.1	9.0	9.3	7.1	29.6%	35.2%	2.7%
Red Meat (total)	4.3	2.8	2.8	5.1	5.6	4.5	5.2	5.6	4.5	5.3	5.5	4.5	21.9%	26.9%	2.9%
Milk	7.7	8.0	7.7	8.4	8.9	8.2	8.4	3.8	8.3	8.4	8.8	8.3	8.1%	13.3%	6.8%
WPRO															
Protein supply quantity (g/capita/day)															
White Meat (total)	11.3	11.7	11.3	13.5	16.0	11.5	14.1	16.3	11.6	14.8	16.3	11.9	30.7%	44.0%	5.1%
Red Meat (total)	8.1	7.6	8.1	9.4	10.0	8.7	9.1	10.0	8.4	9.6	9.9	8.3	18.1%	22.2%	2.0%
Milk	5.7	5.5	5.7	5.9	5.7	5.6	5.9	6.5	5.6	5.9	5.8	5.6	2.6%	0.7%	−2.5%
Global															
Protein supply quantity (g/capita/day)															
Animal	**7.7**	**7.6**	**7.5**	**8.6**	**9.3**	**7.9**	**8.8**	**8.0**	**7.9**	**9.0**	**9.3**	**7.9**	**17.0%**	**20.9%**	**3.0%**

[1] Red meat: bovine meat, mutton and goat meat; White meat: pig meat and poultry meat; Dairy: milk, butter and ghee, and cream; Eggs: Eggs.
[2] BAU = Business as Usual; SSs = Stratified Societies; TS = Towards Sustainability. Data obtained from FAO (2017).

not sustainable on an average global scale, an important question therefore is what level of future demand for animal-sourced food products can be sustainably produced. The answer to this question requires action on both the supply side and on the demand side. While the FAO (2018a) states that 'producing more will be unavoidable, and the way forward is doing so with less', it is not clear what this means on a per capita basis, nor indeed what it means on a regional basis.

The EAT-Lancet Commission (Willett et al., 2019) defined a reference diet that would maintain the health of the consumer and the planet as including, per day, 14 g red meat, 28 g poultry meat, 250 g dairy and 13 g eggs. From their modelling exercise, they concluded that this diet, if consumed by the global population in 2050, would keep climate change within the boundary they set (4.7–5.4 Gt CO_2 –eq/year), but not all their planetary boundaries. Based on the data in Figs. 1–4, the average consumption of these foods in AFRO and SEARO is close to or below the levels in the reference diet while the average consumption of these foods in EURO and PAHO considerably exceeds the reference diet. While the EAT-Lancet Commission reference diet is arguably extreme, its consideration in the light of our analysis highlights the regional variation that exists with respect to the impact of the production of animal-sourced foods on the environment, and thereby underlines the argument that regional/country based strategies are needed to achieve sustainable food systems. In addition, the greater level of under-nutrition and ill health in the less affluent regions, AFRO and SEARO, together with the social and economic benefits of livestock production (Adesogan et al., 2020) indicates that restricting consumption of animal-sourced food to prevent climate change should not be the main strategy in these regions. Such a view also aligns with an often overlooked point of Willett et al. (2019) that 'However some populations worldwide depend on agro-pastoral livelihoods and animal protein from livestock. In addition, many populations continue to face significant burden of under-nutrition and obtaining adequate quantities of micronutrients from plant-sourced foods alone can be difficult. Given these considerations, the role of animal-sourced foods in people's diets must be carefully considered in each context and within local and regional realities' (p11).

Another aspect to be considered in developing strategies on a global basis to address sustainability challenges in that actions in one region may have both positive and negative impacts on other regions. For example, the European Farm to Fork and Biodiversity strategies, which involve targeted reductions in the use of land, fertilisers, antimicrobials, and pesticides, are expected to have significant impacts not only on the competitiveness and productivity of European Union agriculture, they will also affect international markets, and, consequently, the broader food and agriculture system (Beckman et al., 2020). Analysis conducted by the USDA on these strategies highlighted the potentially negative impact of the strategies on vulnerable groups. Considering three different scenarios (adoption of the strategies by Europe only (European Union-only), adoption of the strategies by some countries including explicit European Union trade restrictions against non-adopters (middle), and global adoption), they found that the number of food-insecure people globally would increase by 22 million more than projected without the European Commission's proposed strategies in the European Union-only scenario, i.e. these people would be negatively affected due to decisions and actions that have taken place elsewhere (the number of food insecure would increase to 103 million and 185 million for the middle and global scenarios, respectively) (Beckman et al., 2020).

The outcome of the analysis described above regarding animal-sourced protein consumption to 2050 supports the expectation that per capita demand will increase over time. This analysis also implies significant differences in the regional impact of modifying livestock production systems to be more sustainable. The differences between approaches underlying the "BAU" approach and the "TS" approach are listed in Annex 2 of FAO (2019). To summarise briefly, the prevailing production system for the TS pathway includes higher uptake of low-input precision agriculture, agroforestry intercropping, conservation, climate smart ecological agriculture, and proliferation of the circular economy. Animal welfare and biodiversity are also promoted as important components of the production system. Low GHG emission food systems are favoured and fresh food consumption is advocated in the TS scenario. Additionally, consumers receive information on origin, content, quality, sustainability of processed food. The potential to implement these is unlikely to be the same across regions for a range of reasons including socio-economic, health and cultural factors. The increase in protein demand in AFRO and SEARO and the decrease in EURO and PAHO relative to the 'BAU' scenario are consistent with strategies that could be suggested from the EAT Lancet Commission discussion above. Nevertheless, the global average total animal-sourced protein demand, even in the 'TS' system in 2050, is similar to the baseline 'BAU' in 2012. Given the expected increase in global population, this level of production is not sustainable.

So what options exist to prompt consumers to reduce their consumption of animal-sourced foods on a per capita basis? One option being pursued focuses on developments in science and technology, i.e. offering consumers alternative protein sources. This strategy is promoted by the United Nations, largely through the FAO, with the European Commission also supporting such an approach as demonstrated by significant investment research and development. Alternative protein sources include *in vitro*/cultured meat, insects, seaweeds and single cell proteins (also called microbial proteins) derived from cultures of algae, yeasts, fungi or bacteria (Henchion et al., 2017). In addition, an array of meat substitutes based on plant protein primarily, and reduced meat or hybrid (blend of animal and plant-sourced proteins) products are increasingly available (Henchion and Zimmermann, 2021) and it is likely that a similar transformation will occur in the dairy industry (McClements, 2020). In a review of the current situation, Miller (2020) after consultation with industry anticipates that by 2050, there will be 'localised facilities throughout the world producing cell-based meat, poultry and seafood products to assist in supplying the demand for protein'. While many of these may offer environmental and/or health benefits relative to animal-based proteins, many challenges still exist to their widespread uptake, including technical challenges, food safety concerns, production costs, scalability and sensory barriers. Ensuring that such foods are affordable rather than the preservation of a market segment of concerned citizens with high levels of income is also critical if such developments are not to negatively impact deprived and vulnerable groups. Furthermore, in considering the role of such foods, positive environmental impacts cannot be assumed, and appropriate comparisons need to be made between novel and existing protein sources. Finally, the consequent impact on the dietary intake of non-protein micronutrients that are available in animal-sourced foods when they are replaced by alternatives and whether diets containing such alternatives will require additional supplementation remains to be clarified (Steenson and Buttriss, 2020).

Other options to address demand include policy instruments that influence price, and hence demand (e.g. taxes and subsidies), that address food literacy (e.g. food literacy skill development to support increased use of other foods), and that support consumption of more sustainably produced foods. Carbon taxes can be implemented as an instrument to promote foods that have positive environmental credentials, through providing an economic disincentive to purchasing foods that are detrimental to the environment, with tax revenues also potentially used to promote changes towards diets that are healthy and sustainable (Springmann et al., 2017). However, there are concerns that such taxes could disproportionally negatively affect low-income households, and regions, and thus may not be equitable. An alternative mechanism is to use labelling to encourage consumers to purchase more sustainably produced foods. Research by Camilleri et al. (2019) found that consumers currently significantly underestimate the environmental impact of food and they concluded that 'although consumers' poor understanding of the food system is a barrier to reducing energy use and GHG emissions, it also represents a promising area for simple interventions such as a well-designed carbon label'.

Food based dietary guidelines (**FBDGs**) have also been suggested as a conduit to promoting a more sustainable and healthy diet (IPCC, 2019). However, less than 10 out of 90 countries with food based dietary guidelines have included sustainability measures in their national guidelines (Herforth et al., 2019). Despite a recommendation to limit red meat consumption to a maximum of 500 g a week in Sweden for health and environmental reasons, they also acknowledge that free-range beef and lamb can have positive effects in terms of providing a rich agricultural landscape that ensures that natural pastures are available to benefit species under threat. In Qatar, FBDGs recommend eating healthily while also protecting the environment. In order to achieve this, they suggest prioritizing plant-based foods and reducing excessive consumption overall. In Brazil, a reduction in consumption of animal foods is recommended, with the expectation of a decrease in production and consumption of animal foods, leading in turn to a reduction in emissions of GHGs, intensive use of water, intensive farming and deforestation. More recently, Spain has proposed some measures to update existing guidelines to include sustainability recommendations (Aranceta-Bartrina et al., 2019). These revised FBDG for Spain include recommendations for daily and varied consumption of dairy and meat, while also acknowledging that these foods are in an amber to red zone for sustainability compared to fruit, vegetables and grains, which it positions in the green zone. For the countries that have included sustainability measures in their FBDGs, plant-based foods are prioritised with recommendations to limit red meat, processed meat and dairy. Given that most countries still recommend intakes of animal-sourced foods each day or week, and considering global projections for meat and dairy shown in Table 4, the emphasis therefore needs to be put on the sustainable production of animal foods. Following a 'less but better' approach will fit best with current dietary guidelines in countries that include sustainability measures in their FBDGs, thereby emphasising the need for efficient and sustainable production systems.

Another demand side approach to enhancing the sustainability of animal-sourced foods involves promoting the consumption of more of the animal as food than is the case at present, or more generally consuming more co-processing streams. While consumption of such products, e.g. offal such as liver, heart and tongue, is traditional in some regions, their consumption in EURO for example is limited and has been associated with times of scarcity. A campaign in the United Kingdom called Organuary, organised by the registered charity Public Health Collaboration, promotes the consumption of organ meats due to their nutritional and environmental benefits. Given that the non-meat component of bovine animals accounts for 54–56% of the animal (Marti et al., 2011), such behaviour is likely to be more sustainable. It is supported by a trend towards nose-to-tail dining in high-end butchery and dining establishments in London, for example, for reasons of novelty and sensory appeal. However, ironically, these features also limit its widespread adoption because the lack of familiarity with such foods means that many consumers lack knowledge about how to shop for, prepare and cook these products and concerns about sensory aspects and even the idea of consuming such foods are a barrier (Henchion et al., 2016).

From the production perspective, future livestock systems need to evolve to ensure animal-sourced food products can be 'better'. Livestock production systems vary according to region (Robinson et al., 2011) and have evolved in response to climatic, cultural and economic circumstances. This is evident from Figs. 1–4, where the highest ratio of white meat to red meat is seen in SEARO. It should be noted that white meat contains pig meat and poultry and that white meat in SEARO is likely to be dominated by poultry meat. Modifications to decrease the negative environmental impact and enhance the nutritional value of animal-sourced food products will therefore be context-specific.

Differences in production systems between and within monogastrics and ruminants have important implications for approaches to enhance sustainability. Growth in chicken production globally has been in intensive units specialised in meat or egg production, rather than in backyard systems that tend to raise dual-purpose birds for home consumption and local sale. Pigs, in contrast, are produced in a variety of settings, from small family units through small- to medium-sized commercial, semi-intensive units, to very large intensive units. For ruminant animal-sourced foods, there is a greater diversity of production systems and ruminant livestock species are generally much more dependent directly on the environment in which they live for feed resources than are pigs and chickens. The production context for ruminants is therefore much more dependent on prevailing environmental conditions (Robinson et al., 2011) such as whether ruminants are raised on grasslands (generally considered extensive) or in feedlots (intensive) or whether they contribute to mixed crop-livestock farming systems. Such differences in production systems are relevant in the debate about the potentially negative impact of livestock on food security, particularly when feedstuffs suitable for human consumption are channelled into animal feed. In an extensive study of the food vs feed debate, Mottet et al. (2017) reported that human-edible feed represents about 14% of the global livestock feed ration. Typically, on a global basis, monogastric diets comprise wheat, maize, and soyabean meal while ruminant nutrition is dominated by locally grown forage feeds such as grass and crop residues (Wilkinson and Lee, 2017). When considering only feed materials that are edible by humans, cattle feedlots require the highest ratio of between 37.1 and 44.3 kg human-edible feed/kg protein product. It is also relatively high for industrial pigs, layers and broilers, ranging from 13.8 to 20.0 kg. However, grazing ruminant systems have a substantially lower demand for human-edible feed. Consequently, in a global context, producing 1 kg of boneless meat requires an average of 2.8 kg human-edible feed in ruminant systems and 3.2 kg in monogastric systems (Mottet et al. 2017).

In general, an improvement in the rate of production, whether eggs, meat or milk, and the conversion of feed to these animal-sourced food products will decrease the environmental impact in terms of unit of food/unit of input, including feed/water, etc. Across all species, research has focussed on breeding strategies and improving feed ingredient production and quality, and ration manufacture, to achieve this goal. Across meat species, a variety of growth enhancement technologies are also available which are however not universally approved by regulatory authorities (Moloney and McGee, 2017). An increase in productivity in the face of a limit on demand should result in a decrease in the number of animals required with a consequent decrease in the environmental footprint of these production systems. In addition, advances in manure management in terms of storage, methods of application to land as fertiliser or as a feedstock for energy production also contribute to decreasing the environmental impact of livestock production.

The significant contribution of ruminants to GHG emissions is largely due to methane production during digestion of ingested feed in the rumen. Intensive ruminant production systems have been reported to result in less GHG production (per kg beef) by Capper (2012)) but this issue is subject to debate. Identification of animal-based strategies to mitigate methane production in ruminant production systems *per se* are under ongoing investigation (Adesogan et al., 2020; Henchion and Zimmermann, 2021). In intensive, generally confined, ruminant production systems, research is also ongoing on identifying dietary additives and/or supplements combined with modified feeding practices to decrease methane production. In EURO and PAHO, where ruminant production is more intensive than in other regions, this is a particularly urgent issue. In this regard, GHG mitigation strategies have been shown to reduce emissions by up to 30% (FAO, 2012) and in intensive dairy farms to as low as 1 kg of CO_2 equivalents/kg of energy corrected milk, compared with >7 kg of CO_2 equivalents/kg of energy corrected milk in extensive systems (Knapp et al., 2014).

In temperate climates, pasture-based ruminant production systems may also be considered intensive when compared to pasture-based systems in less favourable climates. In either case, livestock farming is about more than food production; it contributes to many of the sustainable development goals (Peyraud and MacLeod, 2020). Grazing ruminants have a role in maintaining semi-natural habitats, boosting biodiversity, preserving a pastoral landscape that many people value, in nutrient cycling and in sequestering carbon, i.e. in mitigating climate change. Strategies to decrease GHG emissions in these production systems mainly consider grass varieties including multi-species swards, pasture quality, grazing management, and fertiliser type and application methods. The development of crops more resistant to the effects of climate stress (drought, heat, flooding) may also improve the resilience and efficiency of extensive ruminant production.

In extensive pasture-based systems in less developed regions, such as Sub-Saharan Africa and South Asia, low productivity results in higher GHG emission intensities (Adesogan et al., 2020). According to Adesogan et al. (2020), to produce as much milk as the average US dairy cow in a year (10 000 l), about eight Indian dairy cows (producing an average of 1 200 l annually) would be required, generating nine times as much methane. In regions where GHG emissions per unit of food produced are generally higher, sustainable intensification will require practices such as feeding energy dense, nutritionally balanced rations, fertility management, improving genetics, decreasing herd size to retain only productive animals, using appropriate mechanisation, heat abatement and improving herd health. In addition, integration of other operations into livestock production can reduce GHG emissions, and even result in net sequestration of carbon. Complementarity between animal husbandry, crops and forestry offers new possibilities to reduce the negative impact of agricultural production (Peyraud and MacLeod, 2020). From a recent meta-analysis of 86 studies, Feliciano et al. (2018) concluded that silvo-pastoral systems, which involve livestock production in forests, resulted in the greatest net accumulation of soil carbon or net sink of greenhouse gases among agroforestry systems studied. Indeed the soil–plant–animal nexus presents many opportunities for agro-ecological approaches to reduce the negative impact of livestock production (Peyraud and MacLeod, 2020).

A strategy to decrease the negative narrative around animal-sourced foods, and ruminant-sourced foods in particular, is to enhance the nutritional value of the food by modification of the diet of the animal. Considerable focus has been on enhancing those fatty acids considered to be beneficial to human health, such as polyunsaturated fatty acids (**PUFAs**), particularly omega-3 PUFA and conjugated linoleic acid in milk and meat (Shingfield et al., 2013). For example, when compared to concentrates, feeding fresh grass generally results in a higher concentration of omega-3 PUFA in muscle lipids, which contributes to an increase in the PUFA: saturated fatty acid ratio, a decrease in the omega-6: omega-3 PUFA ratio and an increase in the deposition of conjugated linoleic acid (French et al., 2000; Scollan et al., 2014). Grass-finished beef tends towards a higher proportion of cholesterol-neutral stearic acid and less cholesterol-elevating saturated fatty acids such as myristic acid and palmitic acid (Daley et al., 2010). Several studies suggest that grass based diets elevate precursors for vitamin A and E, as well as antioxidants such as glutathione and superoxide dismutase activity as compared to grain-fed contemporaries (Daley et al., 2010). Although the levels of the omega-3 PUFA alpha-linolenic acid, eicosapentanoic acid and docosahexanoic acid are low in ruminant-sourced foods, the levels can be most effectively increased by including them in the ration fed to ruminants and protecting them from rumen metabolism (Noci et al., 2011; Vahmani et al., 2017). Enrichment of ruminant-sourced foods with minerals and vitamin D is currently under investigation (Duffy et al., 2018a). In general, enrichment of monogastric-sourced food is more easily achieved due to the absence of a rumen in which dietary ingredients are fermented. In this regard, the potential of modification of the diet of chickens and pigs to enhance the concentrations of micronutrients relevant to human health in meat has been reviewed (Rooke et al., 2010; Scollan et al., 2017). More recently, Duffy et al. (2018b) demonstrated that dietary supplementation with the maximum allowable level of vitamin D in the diet of pigs substantially increased the total vitamin D activity of pork loin meat.

Table 5 summarises the main discussion points of the paper.

Conclusions

There are increasing concerns about the current sustainability of animal-based foods in terms of both human and planetary health. This has led to a particular focus on animal-sourced protein. Despite the negative narrative around this issue, the ratio of animal-sourced protein to plant-sourced protein has remained relatively constant from 2010 to 2017, albeit with considerable regional variation. However, the predicted increase in per capita protein consumption together with the expected increase in the global population indicates that major changes in animal production and protein consumption are required to ensure future sustainability. A decrease in consumption of conventionally produced animal protein will be encouraged by compliance with FBDG, linked to environmental sustainability, in some countries, and facilitated by the emergence of an array of alternative proteins of plant, insect, algal and microbial origin and cultured animal-sourced proteins. Policy instruments such as carbon taxes may also have a role.

With respect to production of milk, meat and eggs, on the assumption that not all consumers will become vegetarian, i.e., many are not vegetarians by choice (Leahy et al., 2010), and many consumers continue to consume animal-sourced foods because to do so is seen as 'natural, normal, necessary, nice' (Hopwood and Bleidorn, 2019), production of these foods will continue in response to market demand. Livestock production systems vary according to region and have evolved in response to climatic, cultural and economic circumstances. Modifications to such systems to decrease negative environmental impacts and enhance the nutritional value of animal-sourced food products will therefore be context-specific. In general, an improvement in the rate of production, whether of eggs, meat or milk, and the efficient conversion of feed to these animal-sourced food products will decrease the environmental impact in terms of unit of food produced or unit of input, including feed/water, etc. Future livestock production systems will need to be more efficient and exploit available and emerging technologies to achieve this goal while simultaneously mitigating GHG emissions per animal. A list of measures to reduce agricultural GHG emissions with their cost and abatement potential in Ireland is presented in Lanigan et al. (2018). Assuming no change in demand, an increase in productivity should result in a decrease in the number of animals

Table 5
A summary of the main discussion points outlined in this paper.

Item	Point 1	Point 2
Drivers of changed role	Increased role	Reduced Role
	Growing global population	Concerns about health impact of (excessive) consumption
	Increased per capita demand in some regions due to income increases	Concerns about environmental impact of livestock production
	Growing awareness of positive impact of livestock as part of a circular bioeconomy	Concerns about animal welfare
Challenges in maintaining/achieving increased role	Regional imbalances globally in terms of consumption, nutritional adequacy, etc.	
	Globally interconnected nature of livestock systems	
	Trade-offs between economic, environmental and social sustainability	
	Regional variation in ability to implement sustainability strategies	
Solutions	Sustainable intensification (global)	
	Less but better (region specific)	
	Supply	Demand
	Modify livestock production systems	Provide and promote alternative sources of protein
	Integrate management of livestock with other production systems	Reduce *per capita* demand through policies that address price
	Enhance quality of existing animal-based products	Initiatives that promote selection of more sustainably produced products
		Food literacy including FBDG
		More sustainable consumption of whole animal (for food & non-food purposes

required, with a consequent decrease in the environmental footprint of these production systems. In extensive pasture-based systems in less developed regions, sustainable intensification will require modification of feeding practices, culling unproductive animals, fertility management, improving genetics and improving herd health. The importance of grassland for soil carbon sequestration and, at least partially, offsetting gross emissions of ruminants, is also highlighted for other regions including Europe (Peyraud and MacLeod, 2020). In addition, integration of other operations into livestock production can reduce GHG emissions, and even result in net sequestration of carbon. Enhancement of the nutritional value of the food by modification of the diet of the animal is an achievable strategy to challenge the negative narrative around animal-sourced foods.

Most discussions about the need to transform animal-based systems are based on arguments that focus on nutritional and environmental aspects. The analyses conducted in this study demonstrate how transitioning to a sustainable pathway may involve reductions in per capita consumption of animal-sourced protein in high consuming regions of the world alongside increases in lower consuming regions. This emphasises the significance of ethical aspects in relation to any discussions on the future of livestock and consideration of the concept of 'just' transitions. Clearly, the challenge is not merely one for science and technology but one very much based on wider aspects of the food system and its diverse stakeholders.

Supplementary material

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Ethics Approval

N/A, no primary data collected from either human or animal subjects

Data and model availability statement

All data used are freely available from FAOSTAT.

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