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Estimates of optimal supplies of animal-sourced foods differ by food system goal and socioeconomic context

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Reduced consumption of animal-sourced food (ASF) has been recommended for environmental and human health objectives; however, ASF can be important for food security and diet affordability. We explored country-level relationships among various metrics of food supply, socioeconomic context, food security, diet affordability, and agricultural greenhouse gas emissions (GHGe) to characterize how optimal inclusion ranges for ASF vary with socioeconomic factors and food system goals. Data from 2015 to 2022 for 153 countries were sourced to generate Bayesian Networks representing relationships among the studied food system metrics. Networks were used in simulations to characterize optimal ASF inclusion to achieve environmental, food security, or diet affordability goals based on individual country data. Results are most appropriately interpreted in aggregate rather than as representations of specific countries due in large part to data limitations. Across countries simulated, median total ASF inclusion in the food supply to support food security, GHGe, or affordability objectives was 18.2% ± 12.1%, 11.9% ± 6.8%, and 17.6% ± 8.5%, respectively. Joint optimization for these goals resulted in median ASF inclusion of 15.1% ± 7.2%, with notable regional differences. Although ASF increases were supported in most developing regions, decreases were supported in developed countries. The reported SD in optimal ASF inclusion were considerable, and represented between-country variation. Empirical relationships of food categories to goals consistently favored dairy and egg products over meats. These results support previous literature highlighting the environmental intensity of ASF, but also indicate that moderate ASF supplies contribute to multiple food system goals simultaneously.

animal-sourced foods | healthy diet | greenhouse gases

Significance

Reducing animal-sourced foods (ASF) to reduce chronic health disorders and environmental impact has been recommended. However, estimated optimal ASF inclusion varies with food system goals and socioeconomic factors. Median ASF inclusion in the food supply to support food security, agricultural greenhouse gas emissions, or affordability objectives individually or jointly was 18.2% ± 12.1%, 11.9% ± 6.8%, 17.6% ± 8.5% or 15.1% ± 7.2%. Based on the empirical relationships evaluated, more dairy and egg supplies and less meat was suggested, though nutrient adequacy was not evaluated. Optimal country-specific ASF varied considerably, and was affected by incomes, food supplies, and political stability. The multiple critical goals and socioeconomic diversity of food systems require concurrent consideration when identifying optimal ASF supplies and composition.

Society has multiple objectives for its food system related to sustainability, including provision of an adequate, affordable food supply for the global population, and minimized environmental impact. The primary role of the food supply is to provide people with food for healthy diets. A healthy diet is health-promoting and disease-preventing, ensuring adequacy without excess, safeguarding consumption of nutrients and health-promoting substances from nutritious foods, and avoiding consumption of health-harming substances (1). As highlighted in the nutrient guides from numerous national nutritional authorities (2), plant- (PSF) and animal-sourced foods (ASF) are nutritionally complex and complementary for formulation of healthy diets; each contains essential nutrients that the other may not possess in adequate quantities, densities, or bioavailabilities. For example, in describing healthy diets, the World Health Organization (WHO) (3) used ASF to provide 10 to 20% of dietary protein, not simply for their digestible amino acid profile, but to provide essential micronutrients not found in PSF, and to maintain the needed bioavailability of minerals such as calcium, zinc, and iron that may be made less available through effects of phytates or other antinutritional components in PSF; cereal grains and legumes are noted phytate sources (4). Inability to obtain a healthy diet and associated nutritional deficiencies can have their roots not only in the food supply, but in socioeconomic factors, as well (5).

The rapid advancement of climate change (6) and population growth (7) mean that provision of science-based information with which to make decisions on sustainability of food systems and human dietary adjustments is immediately essential (8). There is a critical need to explicitly explore roles of ASF in plant-based diets (those in which PSF predominate) and to recognize that a food system must serve and integrate multiple goals. Toward that end, our objective was to explore country-specific relationships among food supply, socioeconomic context, food security metrics, diet affordability, and agricultural greenhouse gas emissions (GHGe) to characterize how optimal inclusion ranges for ASF vary with socioeconomic factors and food system goals. We hypothesized that these differences

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in food system goals and socioeconomic context would contribute to contrasting conclusions related to global needs for ASF.

As detailed more completely in the Methods section of this work, our analysis leveraged data sourced from 2015 to 2022 on food supplies (9); food security indicators (10); affordability indicators (11); macroeconomic indicators (12); population (13), and agricultural GHGe (14). Variables are defined in Table 1 with notes on abbreviations used. Food security indicators included: stunting, low birth weight (LowBW), obesity, anemia, severe food insecurity (SFI), and undernourishment. Affordability indicators included percentage of the population unable to afford a healthy diet and the cost of a healthy diet (CHD). Macroeconomic indicators included gross domestic product (GDP), gross national income per capita (GNI), and the political stability and absence of violence/terrorism index (political stability). Individual agricultural GHGe (CH_4, N_2O, and CO_2) were used to calculate agricultural carbon footprints using 100 y global warming potentials (15). These data sources were aligned by country and year and used to develop Bayesian Networks [BN (16)] describing the impact of socioeconomic context and food supply composition on food security indicators, agricultural GHGe, and diet affordability. The network structure was learned using a hill-climbing algorithm (17, 18), with blacklisting to ensure arcs between nodes were directed to support the analysis of how socioeconomic context and food supply composition influenced food security indicators, agricultural GHGe, and diet affordability. Network parameters were derived through maximum likelihood estimation (19). For those countries with adequate data (n = 52), unique parameters could be derived for each country, resulting in a country-specific network. For the remaining 101 countries, missing data prevented identification of country-specific parameters and a single set of global parameters were derived. The structure learned for the global network is provided in Fig. 1.

The data used for network structure and parameter learning contained both spatial and temporal elements, and therefore, spatial and temporal autocorrelation was of concern during the derivation of BN. Temporal autocorrelation for the linear associations identified within the BN was tested through a Durbin–Watson test for each relationship within each country for those countries with more than three consecutive years of complete data. Depending on the relationship, complete data were available for between 28 and 143 countries. Across these relationships, only 2 to 8 countries had evidence of autocorrelation ($P \leq 0.05$). The model residuals did not pattern significantly against year, suggesting there was very low impact of temporal autocorrelation on the analysis. Spatial autocorrelation was confirmed ($P < 0.01$) within the data by computing the Moral I statistic for each year of data and each key response of interest (food security indicators, GHGe, and diet affordability). The country-specific BN derived were intended to help address this spatial autocorrelation, and regression of the residuals of the response variables against region showed minimal evidence of bias. The residuals for European countries differed from countries in Central and South America, Western Asia, and Sub-Saharan Africa for food security indicators ($P < 0.05$); however, no other differences in residuals' patterning were detected among regions for these or other response variables. Graphical assessment for the assumptions of normality, constant variance, and linearity showed challenges associated with some extreme points in the prediction of anemia in Jamaica and the prediction of food insecurity in Albania. To explore whether these

Table 1. Abbreviations and definitions

Anemia	Percentage of reproductive-age women with anemia
ASF	Animal-sourced foods
BN	Bayesian networks
CHD	Cost of a healthy diet, US $
GDP	Gross domestic product
GHGe	Agricultural greenhouse gas emissions, including CH_4, N_2O, and CO_2
GNI	Gross national income per capita
LowBW	Percentage of children born with low birth weight
Obesity	Percentage of children under 5 y of age who are overweight
Political Stability	Index of political stability and absence of violence/terrorism
Inability to afford a healthy diet	Percentage of population unable to afford a healthy diet (PPUAHD; affordability)
PSF	Plant-sourced foods
Stunting	Percentage of children under 5 y of age who are stunted
SFI_Fa	Rolling 3-y average percentage of females experiencing severe food insecurity
SFI_Ma	Rolling 3-y average percentage of males experiencing severe food insecurity
Undernourishment	Rolling 3-y average percentage of the adult population whose habitual food consumption is insufficient to provide dietary energy levels required to maintain a normal, active healthy life

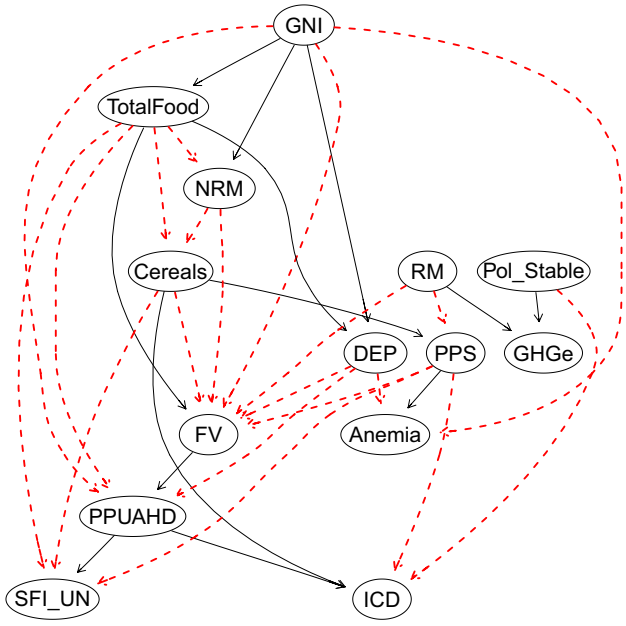

Fig. 1. BN describing directed associations among agricultural GHGe, prevalence of anemia, childhood diseases (ICD, the sum of low BW, childhood obesity, and stunting prevalences), SFI and undernourishment (SFI_UN, sum of 3-y rolling average metrics for food insecurity among adult males and females), proportion of the population unable to afford a healthy diet (PPUAHD), GNI, political stability and lack of violence/terrorism (Pol_Stable), per capita food supply (TotalFood), and proportions of food supply coming from ruminant meat (RM), nonruminant meat (NRM), dairy and egg products (DEP), cereals (Cereals), fruits and vegetables (FV), or plant protein sources (PPS). Dashed red lines indicate inverse associations while black solid lines show direct associations.

points would hold considerable influence on the analysis, we repeated the analysis with and without the data from Jamaica and Albania. The resulting simulation medians differed by <5% on average suggesting that the points did not change the interpretation of results. As such, the analysis is presented using all available data. Interpretation of data for individual countries should be done with caution as data challenges limit confidence in our ability to accurately replicate specific country behaviors. However, the aggregate distribution of responses across countries can be interpreted to reflect likely system responses given the initial conditions reflected by country-specific political stability, economic context, and food supplies. For this reason, we focus on interpreting data as distributions reflecting food system behaviors, and avoid interpretation of individual country responses.

Results

The BN were used to explore how shifting country-specific food supplies would influence food security indicators, GHGe, and diet affordability through a simulation approach. Specifically, for each country, the BN were used to generate predicted food security, GHGe, and diet affordability outcomes from 22,050 theoretical food composition scenarios representing different inclusion levels of total ASF (from 0% of total food to 1.5 times the country's current ASF supply), and different composition of ASF [ranging from 0 to 100% of ASF coming from ruminant meat (RM), non-ruminant meat (NRM), and dairy and egg products (DEP)]. In each scenario, the country-specific standardized difference between the predicted outcome and current observed level of that outcome was calculated. Optimal scenarios for individual objectives were identified as those which resulted in the minimum (most negative) standardized difference for the outcome of interest in that optimization. In many cases, a range of optimal scenarios were identified because all resulted in the same standardized difference. From this set of optimal ASF inclusion and composition, the scenario reflecting the median ASF inclusion was used for primary analysis (Fig. 2); however, scenarios reflecting the minimum and maximum ASF inclusion were also recorded to better understand the range of

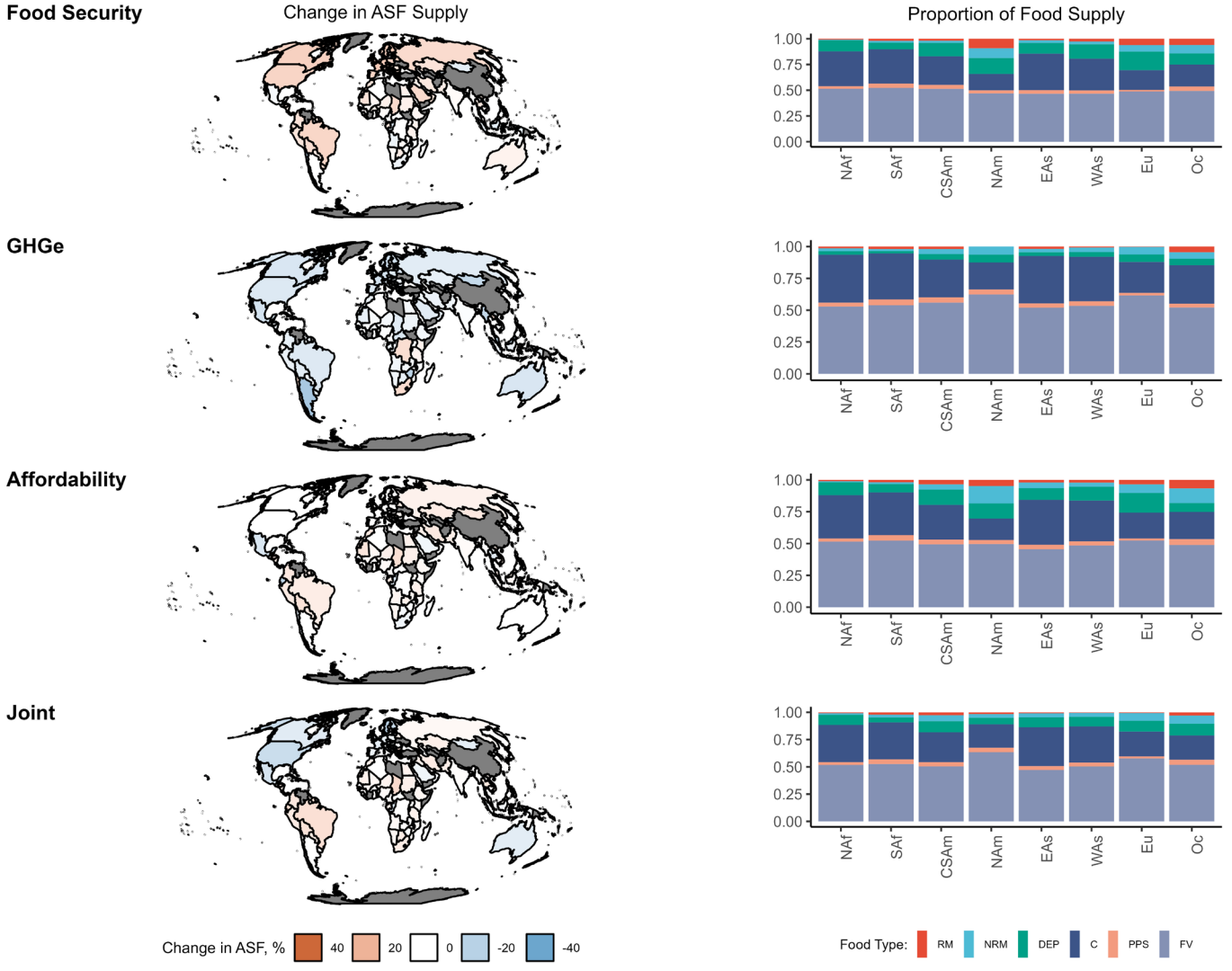

Fig. 2. Simulated change in ASF supply associated with minimizing instances of different outcomes (map) and region-specific balance (bar chart) of RM, NRM, DEP, cereals (C), FV, and PPS. Food system supply proportions were summarized by region for northern Africa (NAf), Sub-Saharan Africa (SAf), Central and South America (CSAm), Northern America (NAm), Eastern Asia (EAs), Western Asia (WAs), Europe (Eu), and Oceania (Oc). Simulated outcomes were for minimizing food insecurity; minimizing GHGe; minimizing the PPUAHD (Affordability); and optimizing to jointly minimize the PPUAHD, GHGe, and food insecurity. Change in ASF reflects the percentage change in animal source food supplies relative to current supplies in the optimal scenario identified with the median total ASF supply. The bar charts reflect the proportion of food supplies (*y*-axis) associated with each food category in that scenario.

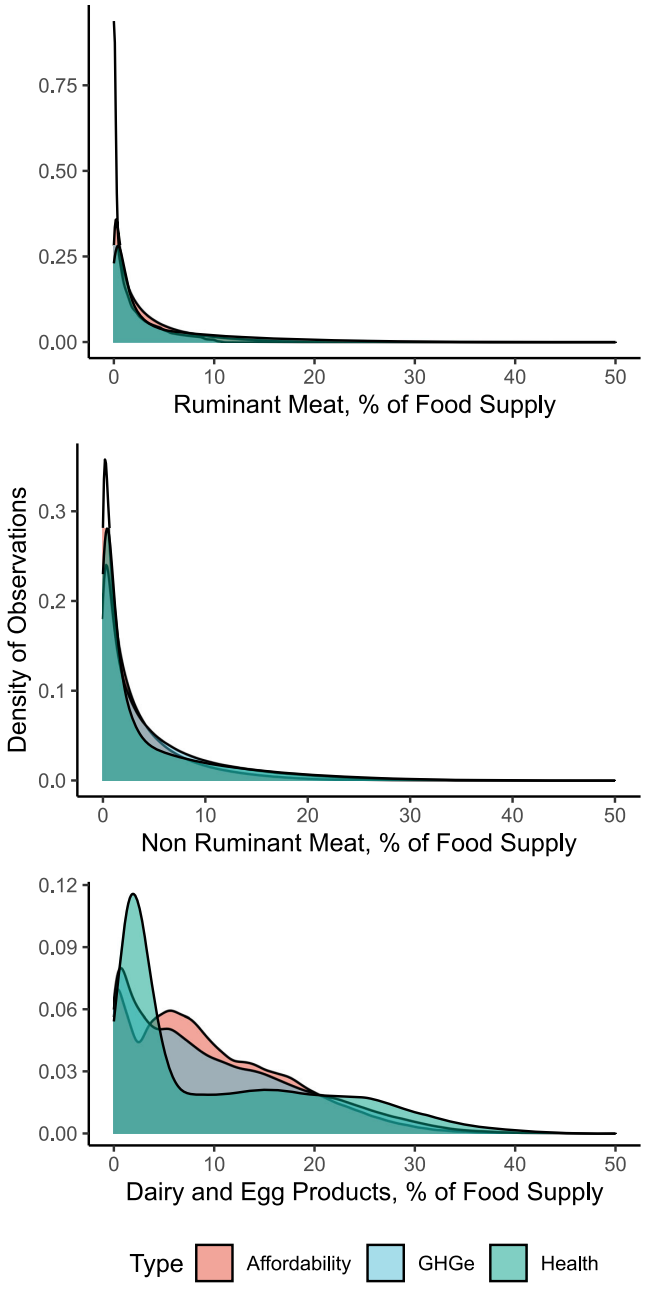

Fig. 3. Distribution of RM, NRM, and DEP as a percentage of the food supply within countries during scenarios identified as supporting optimal diet affordability, agricultural GHGe, or food security outcomes. Graphs reflect the density of observations (*y*-axis) observed at each percent of ASF inclusion in the food supply.

relatively equivalent scenarios. The distribution of ASF composition across all scenarios identified as optimal for each objective is included in Fig. 3. Variation in optimal ASF due to socioeconomic context is shown in Fig. 2, while Fig. 3 represents variation in optimal ASF due to uncertainty in our ability to define unique and precise relationships within the food system.

The median current ASF supply across countries calculated within the present study was 15.4% ± 8.1% ASF (*SI Appendix*, Figs. S1 and S2). The median ASF inclusion in the food supply to support food security, GHGe, or affordability objectives across countries was 18.2% ± 12.1%, 11.9% ± 6.8%, and 17.6% ± 8.5%, respectively (Fig. 2). The SD reflects the variation among medians identified across the countries simulated. When summed based on individual country population, food supply, and target ASF, these median ASF inclusion levels reflect a 37.2% increase, a 23.5% decrease, or a 14.4% increase relative to current global ASF supplies, respectively. Joint optimization of these goals resulted in ASF inclusion of 15.1% ± 7.2% (Fig. 2), equivalent to an 8% reduction from current supplies.

Reductions in NRM (−30 to −66%) and RM (−9 to −74%) were supported in median optimal scenarios irrespective of goal; however, the distribution was extremely skewed with the majority of optimal scenarios containing negligible amounts of meat (Fig. 3). Reductions in meat were offset by increased supplies of DEP (15 to 221%), with a more uniform, though still skewed, distribution of inclusion (Fig. 3). In addition to considerable variation among countries and food system objectives, there was also variation in outcomes that can be attributed to uncertainty in defining quantitative relationships among food supply, socioeconomic context, GHGe, and diet affordability (*SI Appendix*, Figs. S3 and S4). Distributions of ASF ranging from 12.5 ± 8.6% to 19.8 ± 10.4% were identified as roughly equivalent for working toward affordability objectives (*SI Appendix*, Figs. S3 and S4). The range of GHGe minimizing scenarios was greater, with distributions ranging from 0.00 ± 5.3% to 22.1 ± 12.2% (*SI Appendix*, Figs. S3 and S4).

The uncertainties in outcomes are largely driven by the limited number of relationships identified within the network. The BN identify a parsimonious set of associations, in part, because of the covariation among variables. Specifically, food supplies are represented as percentages, meaning that when one food group is reduced, the percentages of others are increased, creating considerable covariation by calculation among food supply variables. As such, a relationship between fruits and vegetables (FV) and diet affordability, for example, has both direct and indirect elements. The relationship represents a direct link between FV supplies and the percent of the population able to afford a healthy diet, but also includes intrinsic covariation reflecting the food system changes that typically occur with shifts in fruit and vegetable supplies. This covariation is unavoidable within the data and reflects a limitation of food system analyses based on historical data. Explicit studies on food system substitutions or structural changes are needed to generate data necessary to support improved quantitative understanding of how food supply changes influence capacity to achieve food system objectives. Until these more intentional data generation exercises are conducted, it will continue to be challenging to isolate how production of specific foods supports food security, GHGe, or affordability goals at the food system scale.

It is important to note that irrespective of total ASF inclusion in GHGe minimizing scenarios, RM production was minimized. In the few countries that retained RM within the optimal GHGe minimizing scenarios, unique country-specific network coefficients drove this inclusion. Specifically, the results for 13 countries with negative coefficients relating RM supplies to decreased GHGe were driven by distinct country-specific dynamics that mask the mechanistic links between RM and GHGe. For example, in both Chile and South Africa an inverse association between RM and GHGe was found, with the raw data for these locations showing the lowest GHGe in years with the highest RM supply. Undoubtedly, this trend in the data is driven by other parameters not well captured within the network analysis. Rather than supporting some unique production practices within these areas, this paradoxical lack of association between RM and GHGe more likely reflects specific socioeconomic factors within those countries during the short timeframe from which data were collected. It is an additional limitation of the BN approach that significance of associations will be assigned based on the variables included and may not reflect mechanistic associations among those variables, but rather associations with

unexplored covariates or lurking variables. Continued investigation into these anomalies in food systems data may help to identify the types of additional variables that should be included in future analyses to work toward more mechanistic understanding of food system behaviors.

To explore how network results are supported by underlying relationships within the data, Pearson correlation coefficients between per capita food category supplies, nutritional health and food security indicators, and socioeconomic factors were calculated (Fig. 4). Correlations for some food supplies and food system outcomes could be swayed by influential points (*SI Appendix*, Figs. S5 through *SI Appendix*, Fig. S13) yet still followed the general directional form of the majority grouping of the data. Removal of influential points for Lamb, Veal, and Game Products and Nut and Seed Products changed statistical significance in five cases, but the sign on the correlation changed in only 1 (*SI Appendix*, Fig. S1 through *SI Appendix*, Fig. S13). Per capita ASF food supplies were generally moderately negatively correlated with food insecurity metrics, which aligned with ASF inclusion in food supplies optimized toward food security. The pattern of correlations was largely the inverse of this for childhood obesity, which is a disease of excess. This divergence was likely masked in scenario results because food security was treated as a single, combined objective based on weighting prevalence of food insecurity, anemia, and childhood diseases equally. Per capita ASF supplies were inversely associated with inability to afford a healthy diet (Fig. 4) agreeing with greater ASF inclusion in scenarios with affordability objectives. Per capita ASF supplies were also positively associated with political stability and GNI, with political stability and GNI being negatively correlated with inability to afford a healthy diet, but positively correlated with each other (Fig. 4). The networks used for simulations should account for these confounding influences of socioeconomic context; however, the correlations suggest that socioeconomic context may be a major driver of the variability of ASF inclusion rates identified as optimal in the scenarios.

Regression of proportional costs of foods in least-cost healthy diets against political stability showed a decline for ASF as political stability increased (slope of −7.9 and R^2 = 0.26; *SI Appendix*, Fig. S14) suggesting a decline in the cost of ASF as political stability improved. Respective slopes and R^2 values for other food categories showed weaker relationships with political stability, and variable directionality of the slopes (slope, R^2: starchy staples, −5.4, 0.07; vegetables, 4.2, 0.08; fruits, 4.9, 0.11; legumes, 4.9, 0.06; *SI Appendix*, Fig. S14).

Discussion

A primary goal of this work was to explore how socioeconomic context influenced optimal ASF inclusion under varying food system goals. The answer we arrive at depends, in part, on the question we ask. Optimal ASF inclusion varied with food system objectives, and across different socioeconomic contexts represented by country-specific GNI, political stability index, and total food availability (Fig. 2). Divergence in ASF inclusion among scenarios suggests that unique food system priorities require individual solutions, and that solutions may differ in efficacy across the diverse global population whose diets are affected by food availability, wealth, education, and other socioeconomic factors (5, 20). The range of scenarios identified as optimal for given objectives and countries reflects uncertainty in our understanding of country-level pressures which influence optimal ASF inclusion. More specific exploration of this uncertainty should be the objective of future work.

The optimization outcomes suggested that minimizing agricultural GHGe would recommend reductions in ASF supplies relative to today, which largely agreed with previous studies concluding that reducing ASF from current levels will help to mitigate agricultural GHGe (21–23). The ASF included in the GHGe minimizing scenarios favored DEP over RM, which reflects the lower environmental footprints of dairy and eggs compared with meat in traditional life cycle assessments (24, 25). However, it is important to note that cull dairy cows, male calves, and surplus female calves contribute to RM supplies, just as cull-laying hens contribute to NRM supplies. Food systems containing DEP will contain meat coproducts; this should be addressed in future, mechanistic studies on food system feasibility related to this suite of goals.

Food security-focused scenarios in the present work supported global increases in ASF, suggesting ASF are important to food security. This aligns with several previous reviews focused on food security metrics as related to essential nutrients provided by ASF and the importance of context (e.g., developed vs. undeveloped countries, economically marginalized populations, low and

Food category or factor	Obesity	Stunted	Anemia	Low birth weight	Under-nourish-ment	SFI_Fa	SFI_Ma	Inability to afford a healthy diet	Cost of a healthy diet	Political stability	GNI
Animal-sourced foods											
Lamb, veal, and game products	0.11	-0.02	0.03	-0.11	-0.05	-0.003	0.01	0.10	0.02	0.01	0.002
Beef products	0.38	-0.26	-0.39	-0.42	-0.01	-0.21	-0.23	-0.32	-0.21	0.16	0.34
Dairy and egg products	0.29	-0.64	-0.58	-0.62	-0.51	-0.51	-0.51	-0.69	-0.27	0.54	0.70
Pork products	0.15	-0.49	-0.61	-0.55	-0.26	-0.50	-0.49	-0.63	-0.13	0.53	0.54
Poultry products	0.43	-0.63	-0.55	-0.15	-0.42	-0.31	-0.33	-0.61	0.15	0.44	0.36
Sausages and luncheon meats	0.14	-0.35	-0.28	-0.22	-0.12	-0.25	-0.26	-0.28	0.11	0.36	0.13
Plant-sourced foods											
Cereal grains and pasta	-0.07	0.19	0.37	0.36	-0.32	0.07	0.07	0.25	0.01	-0.44	-0.41
Baked products	0.28	-0.40	-0.44	-0.39	-0.18	-0.29	-0.30	-0.41	-0.07	0.47	0.47
Breakfast cereals	0.27	-0.37	-0.50	-0.29	-0.09	-0.29	-0.30	-0.41	-0.07	0.51	0.52
Vegetables and vegetable products	0.07	0.01	0.08	-0.19	-0.04	-0.02	0.00	0.03	-0.06	-0.07	-0.06
Fruits and fruit juices	0.30	-0.30	-0.19	-0.16	-0.29	-0.09	-0.11	-0.19	0.10	0.13	0.01
Legumes and legume products	-0.19	0.40	0.21	0.20	0.16	0.29	0.31	0.37	-0.14	-0.28	-0.25
Nut and seed products	-0.08	-0.10	0.09	0.08	-0.09	-0.09	-0.10	0.07	0.14	0.072	-0.07
Socieoeconomic factors											
Inability to afford a healthy diet	-0.51	0.87	0.73	0.63	0.59	0.71	0.72	1.00	0.17	-0.62	0.17
Cost of a healthy diet	0.04	-0.09	0.06	0.24	-0.25	0.10	0.03	0.17	1.00	0.04	-0.26
Political stability	0.25	-0.63	-0.59	-0.39	-0.23	-0.33	-0.35	-0.62	0.04	1.00	0.58
GNI	0.28	-0.56	-0.61	-0.47	-0.40	-0.43	-0.43	-0.62	-0.26	0.58	1.00

Fig. 4. Pearson correlation coefficients for per capita food supply of food categories, prevalence of diet-related diseases, food insecurity, and socioeconomic factors. Values in orange are positive correlations, blue are negative, and white are not significant. Abbreviations: GNI, gross national income per capita; SFI_Fa or SFI_Ma, SFI for women or men, respectively, percentage of population, other definitions are in Table 1; *P*-values: $P \le 0.05$, $0.05 < P < 0.10$.

middle vs. high income countries) (26–28). Food security, however, is only one component of nutritional health, and numerous previous studies reliant on simulations or models of food systems data have recommended reducing global ASF production in support of human nutritional health (21–23, 29), particularly as related to nutritional diseases of excess (i.e., cardiovascular disease, diabetes, and cancer). The discordant conclusions within the literature around ASF and health are partially due to focus on nutritional diseases of excess vs. food security indicators which reflect nutritional diseases of insufficiency of total food or specific nutrients (30). The role of ASF in minimizing deficiency-related diseases is supported by elevated concentrations of required micronutrients in ASF, higher bioavailability of minerals and amino acids in ASF (3, 31, 32), and dilution of antinutritional factors from PSF (33). Ironically, links between high ASF intakes and prevalence of nutritional diseases of excess (34, 35), are likely also due to the nutritional density of ASF. In popular forms such as ground meats, ASF has higher energy and saturated fat concentrations compared with many other protein substitutes (36). To balance the nutritional benefits and challenges of ASF, reference diets (37–39) designed to maintain nutritional adequacy and minimize excess often conclude that low to moderate daily ASF intake, with the majority of that intake coming from DEP, are supportive of human nutritional health goals. These dietary frameworks stress moderation, which is supported by previous work focused on macronutrient ratios, highlighting optimal macronutrient ranges for minimizing health risks (40, 41). Although food system composition (i.e., supply) differs from diet composition due to trade, waste and loss, and nonfood uses, food access, food choice/preference, and other factors, it is of note that all these ASF supply ranges identified as optimal fall within the WHO recommended 10 to 20% ASF necessary for a healthy diet (3). Although more robust studies at the intersection of health, dietary adequacy, and ASF supplies are warranted, this study, and the literature more broadly, supports low to moderate ASF supplies for food security and health objectives. A limitation of the present study, and much of the similar literature, is that only empirical relationships between foods and food security metrics were considered. Future analyses of food security should consider what nutrients are required from foods to meet comprehensive and specific nutritional requirements that vary with age, gender, physiological stage, and population size and dynamics. This more nutritionally focused analysis is important to dictate inclusion of foods or supplements that supply nutrients in adequate quantity and bioavailability.

Diet affordability optimization supported a slight global increase in ASF inclusion, which agreed well with a previous review (42) and studies (43–45) highlighting complementary roles of ASF and PSF in affordable diets as assessed with the Nutrient Rich Foods Index (45) and linear programming to determine least-cost nutritionally adequate diets for adults (43, 44). Within the diet affordability scenario, there was considerable between-country variation in ASF inclusion. Increased ASF supplies occurred primarily throughout the developing world, and reductions were simulated in the developed world. These regional differences are supported by specific intervention studies in developing countries exploring the interplay among ASF supply, household economics, and nutritional adequacy. For example, a project in Zambia compared households that received a dairy cow, draft cattle, or meat goats to those that did not. The former households had increased dietary diversity, an indirect measure of diet quality, increased food security, and improved household income (46); though impact varied with the type of livestock received (47). Similarly, vaccination of small-scale chicken flocks in Tanzania for Newcastle disease, a fatal disease of chickens, resulted in increased food security in the project households as compared to control households (48). These studies empirically demonstrate that livestock and associated ASF can provide food or income, supporting food security and improved economic independence (49). It is well recognized that as income rises, populations increase consumption of ASF (50), which is also associated with progression from nutritional deficiency diseases to diseases of nutritional excess (51). Covariation among these factors suggests that much like what was discussed for food security goals, there likely exists a low to moderate level of ASF supply to support affordability while minimizing risk of over- and undernutrition.

Socioeconomic context was impactful in the scenario jointly optimizing GHGe, food security, and diet affordability (Fig. 2). Although increases in ASF were optimal in many developing regions, reduced ASF supplies were recommended in most developed countries (Fig. 2). This imbalance of nutrients coming from global ASF supplies has been highlighted in previous studies (52, 53). Assessments of global beef demand suggest that global trade is already redistributing ASF as demands shift (54); however, the broader impacts of trade on food sovereignty (55) and environmental externalities (56) are important to consider. In addition to highlighting the importance of socioeconomic context in identifying optimal ASF inclusion, country-specific differences also highlight the importance of different goals by country. Incidence of food insecurity is less pronounced in developed regions; however, these countries also have considerably higher GHGe. Thus, scenario outcomes in developed countries favor those which support GHGe minimization, while developing country outcomes favor food security and affordability objectives above GHGe. Irrespective of location, scenarios focused on joint optimization relied primarily on DEP, rather than meat. Dairy foods and eggs have consistently been highlighted as important to supporting affordable healthy diets (57, 58). When compared on a protein equivalent basis, meat and nonmeat products have similar cost (36); however, in an evaluation of least-cost diets for individual countries, meat made up an average of only 30% of ASF included in diets (59). As noted above, increased reliance on DEP will also support GHGe objectives; however, inclusion of meat coproducts and their role in meeting nutritional needs requires further evaluation.

A limitation of this work was the available data for network derivation. Few countries had sufficient data to support derivation of country-specific BN, and many countries had limited years of data available, precluding intentional analysis of the available time series of data using the existing approach. It is clear from the residuals analysis that some responses in some countries may not be well represented with the current BN. As such, rather than interpreting the data in terms of specific country responses, it is most appropriate to consider the results in aggregate, with countries treated as elements making up the broader food system distribution.

Conclusions

We explored country-level relationships among food supply, socioeconomic context, food security, diet affordability, and agricultural GHGe and identified that optimal inclusion ranges for ASF vary considerably with socioeconomic context and food system objectives. Based on the empirical relationships inherent in the available data, low to moderate ASF inclusion (15.1% ± 7.2%) supported joint optimization of food security, diet affordability, and GHGe objectives. This scenario included marked reductions of ASF in some regions and increases in others. Future work should explore knowledge gaps that contribute to uncertainty in quantifying relationships among food system factors; generate more comprehensive food systems datasets; investigate food

system interventions and identify mechanistic relationships; assess actual nutrient sufficiency of food supplies; and investigate paradoxical results as a way to drive new data collection efforts. Each of these advancements in our tools for studying food systems will be essential to more reliable and comprehensive study of the feasibility of and challenges expected in transitioning toward country-specific food system targets.

Materials and Methods

Data Sources, Cross-Referencing, and Preparation. The FAO Stat database was used to source data on: 1) food supplies (9) for agricultural and food commodities; 2) food security indicators (10); 3) cost and affordability of a healthy diet (11); 4) macroeconomic indicators (12); 5) population (13); and 6) agricultural GHGe (14). Information was sourced for all available countries between 2015 and 2022 and organized by country and year. Of available agricultural production data, food supplies were retained as the value of greatest interest for the analysis. Of the available food security indicators, Stunting, Overweight, LowBW, Anemia, Undernourished, SFI_Ma, and SFI_Fa were retained. Of those available macroeconomic indicators, GNI (per capita, standardized), GDP (US$), and political stability were retained. Of the available metrics of the cost and affordability of a healthy diet, the CHD (US$) and percentage of the population unable to afford a healthy diet were retained. Agricultural emissions of CO_2, N_2O, and CH_4 were retained for analysis and used to calculate total agricultural GHGe based on 100-y global warming potentials (15). Other relevant metrics within the FAO database were omitted due to limited data availability. Although the FAO database includes food supply estimates for beverages, fats and oils, finfish, and shellfish products, snacks, spices and herbs, and sweets, supplies of these food categories were not included in the present analysis due to the focus on staple crops and terrestrial ASF.

A cross-reference to match commodity names in the food supply data with names of foods in the USDA Foods database (60) was developed to assign food categories to each commodity. Total mass of each food category was calculated by summing within food category, country, and year. Food supply data were merged by country and year with the food security indicators, cost and diet affordability metrics, macroeconomic indicators, population data, and GHGe. Annual commodity supply totals were divided by population to yield per capita commodity estimates for each country.

Structure Learning. A BN was developed using food security indicators, cost and diet affordability metrics, macroeconomic indicators, GHGe and food category supply descriptors as nodes ($X_1 \ldots X_n$) where each node can be indexed as an individual, i, of the 14 variables (i.e., $n = 14$) considered in the analysis. The network structure, reflecting the dependence structure of relationships among these nodes, was defined through a directed, acyclic graph (G), such that

$$P(X|G,\theta) = \prod_{i=1}^{n} P(X_i|\Pi_{X_i},\theta_i),$$

where the global distribution of nodes (X; $n = 14$) with parameters θ is decomposed to individual local distributions for each X_i with parameters (θ_{Xi}) conditional on the parents, Π_{Xi}, of X_i(61). The purpose of the network was to explore how socioeconomic context and composition of the food supply influenced food security, agricultural GHGe, and diet affordability. Food security metrics were condensed to three variables representing childhood diseases (the sum of Obesity, Stunting, and LowBW), anemia in reproductive-aged women, and average percent of the adult population experiencing food insecurity or undernourishment. Food supply was represented by simplified food categories, including per capita supplies of cereals (C), FV, plant protein sources (PPS), RM, NRM, and DEP. The BN was selected due to its strength in exploring complex interactions within natural systems, capacity to investigate tradeoffs within those systems, and reliance on directed relationships intended to imply a greater degree of causality (62) than can be inferred from analyses based on correlation (63). Further, the ability of the BN to learn the structure of relationships within the data as a directed, acyclic graph (64) was a key advantage for this analysis to allow a compromise in the number of researcher-imposed assumptions about the possible relationships that existed among food supply, socioeconomic, food security, GHGe, and affordability variables. Given the objective, a central focus during the network development process was to ensure the approach was as data-driven as possible while still allowing for exploration of how socioeconomic context and food supply composition influenced food security, agricultural GHGe, and diet affordability.

The bnlearn package (16) of R v 4.3.1 (65) was used to learn the network structure using the hill-climbing algorithm (17, 18), implemented through the hc function of the bnlearn package. During the initial phase of analysis, several structure learning algorithms were compared, including constraint-based (incremental association, grow–shrink, max–min parents and children) and hybrid (min–max hill- climbing) algorithms. Constraint-based algorithms are often favored over score-based algorithms due to their emphasis on prioritizing causal structure; however, score-based algorithms apply general optimization techniques to the structure learning, resulting in networks that are generally more accurate (61). We selected a score-based algorithm for use in this analysis for two reasons. Primarily, the use of the network for simulation required prioritizing accuracy to achieve the greatest confidence in using the network to simulate food systems. Secondarily, a preliminary testing of different constraint-based (incremental association, grow–shrink, max-min parents and children) and hybrid (min–max hill-climbing) algorithms revealed identified network structures that were only partially directed requiring researcher intervention to dictate arc directionality. These networks also identified fewer relationships among food system variables, making their use for this simulation challenging. As one goal of the analysis was to keep the network as data-driven as possible, the avoidance of researcher-directed arcs was preferred. It is critical to note that these methodological choices undoubtedly influence the relationships identified within networks and resulting inferences from data simulated by these networks. Therefore, the results of this study reflect only one representation of the possible relationships held within these data.

In fitting the network structure, a number of arcs were blacklisted a priori. Blacklisting restricts the inclusion of particular arcs during the structure learning process. Blacklisted relationships were identified based on the intended use of the network, namely, to explore how socioeconomic context and food supply composition influenced food security, agricultural GHGe, and diet affordability. Relationships to the food supply nodes (cereals, PPSs, DEP, RM, FVs, and NRM) from the intended outcome variables (food insecurity prevalence, anemia prevalence, incidence of childhood disease, diet affordability, and agricultural GHGe) were blacklisted because a prevailing assumption of this work was that food security, GHGe, and diet affordability were at least partially dependent on food supplies. We also restricted GNI and political stability to be driving variables in the network (i.e., not conditionally dependent other variables) because the intent of the analysis was to explore associations of food supplies, food security, affordability, and GHGe within socioeconomic contexts represented by GNI and political stability. As a final restriction, GHGe were considered conditionally independent of food security metrics to support identification of direct linkages between food supply and GHGe. Blacklisting arcs within the network was done to ensure the network structure allowed us to explore the objective of the study, however, these blacklisted relationships are expected to influence study outcomes and the need for blacklisting is a limitation of the present work. For example, in reality, there is likely a feedback loop between agricultural system activities and socioeconomic indicators such that larger agricultural systems contribute to greater GNI and improved political stability, and vice versa. Therefore, it is possible that by forcing directionality from socioeconomic indicators to other food system metrics we may unintentionally inflate or mask the true influence of these factors within the systems context. The same may be true for other blacklisted relationships.

Parameter Estimation. Although BN are commonly used to handle discrete data, the nodes used in this network were retained as continuous data, meaning that a Gaussian BN was derived. Specifically, following Geiger and Heckerman (66) we assumed that X_i behaves as univariate normal distributions linked with linear dependence to Π_{Xi} such that

$$X_i|\Pi_{X_i} \sim N(\mu_{X_i} + \Pi_{X_i}, \beta_{X_i}, \sigma^2_{X_i}),$$

where β_{Xi} and σ^2_{Xi} reflect the slopes and residual errors, respectively, of the linear regressions relating X_i and Π_{Xi}. These parameters were fit via maximum likelihood estimation using the bn.fit function of the bnlearn package.

Handling Location Specificity in Networks. It is likely that unique country-specific factors and historical context influence the relationships between food

supply composition and food security, agricultural GHGe, and diet affordability in a manner not comprehensively captured by relationships held more globally with GNI and political stability. As such, we also explored inclusion of a categorical country node within networks. This categorical country node allowed unique β_{Xi} and σ^2_{Xi} to be derived for each specific country for pairings of X_i and Π_{Xi} where one parent was Country. Despite having the strength of better representing individual contexts within a country, this fitting approach required complete observations for all variables within the dataset to reliably estimate β_{Xi} where necessary. The dataset used for structure learning and parameter estimation had numerous missing observations. Of 153 countries, 52 (primarily developing) countries had sufficient data to derive individual network parameters. These missing data meant that the inclusion of a country node restricted the data used in structure and parameter learning to include only those data from the 52 countries with complete information. Thus, to make more complete use of the available data, two model structures were learned and two sets of parameters were estimated, following the logic akin to the IPCC tiers (15). During the structure learning process, the global network structure was derived first, and the country-specific network structure was then learned as an update to that global network structure. This was accomplished by whitelisting the global network structure, adding the country node, and learning edges where country should interact within the global network structure. During the parameter estimation process, the global network parameters were estimated based on all available data. The country-specific network parameters were learned only for those 52 countries with complete data. In both cases, parameters were estimated by maximum likelihood. In the country-specific networks, socioeconomic context is defined by country, GNI, and political stability, while in the global network, socioeconomic context is defined only by GNI and political stability. Thus, the primary difference between approaches was the data used (available data from all counties vs. data from 52 countries with complete observations) and the inclusion of a categorical node representing country during the structure learning and parameter estimation process.

Simulation of Food Systems. To explore how shifting the composition of the food supply within individual countries might influence food security, agricultural GHGe, and diet affordability, a simulation approach was leveraged. Simulations were conducted by country. For each country, the appropriate network (country-specific or global) was used to simulate 22,050 theoretical food production systems. Each simulation used the mean political stability, GNI, and total food supply to initiate the network. The mean food proportion data for that country were then adjusted to simulate ASF supplies ranging from 0% of total food to 1.5 times the current proportion of ASF in the total food supply, by weight. This range was selected to center adjustments in ASF supplies around current ASF production, given the considerable global variation in ASF as a percentage of total food supply. Within the range of 0 to 1.5 times current ASF supplies, 50 evenly spaced possible ASF supply rates were selected for simulation. Within each ASF inclusion rate simulated, different balances of DEP, RM, and NRM (0 to 100% by 5% increments for each product) were tested, such that S is the set of resulting scenarios for an individual country, that can be defined as

$$S = \left\{ (t, d, r) \,|\, t \in (0, \cdots, 1.5xT), d \in (0, \cdots, 100), r \in (0, \cdots, 100) \right\},$$

where, for each scenario, t reflects the total proportion of ASF in the food supply, T refers to the current proportion of ASF in the food supply, d reflects the dairy and eggs as a proportion of ASF (ranging from 0 to 100), and r reflects the RM as a proportion of ASF. Notably, scenarios were restricted from all possible to only those scenarios where $d+n+r = 100$ by expressing n, the proportion of ASF as NRM, as 100-d-r. Through this approach, each S also has emergent properties reflecting the remaining food supplies reflected by n, as all well as f, FVs, c, cereals, and p, plant proteins. As ASF increased or decreased relative to the mean current ASF for the country, the PSF within the food supply was reduced or increased proportionally, following:

$$f = \frac{-f}{(-f + -c + -p)} \times (100 - t),$$

where $-f$, $-c$, *and* $-p$ reflect the current mean inclusion of those food categories in the country's food supplies. Here, fruits are used as an example and the same equation is applied to cereals and plant proteins.

The resulting simulations created 22,050 complete cases for each country to independently explore how proportion of ASF within the food supply and the balance of ASF types influenced food security, agricultural GHGe, and diet affordability. Food supplies were used as inputs to the network along with the mean political stability, GNI, and country (in the case of country-specific network use) to predict expected food security, affordability, and environmental outcomes under each simulated food supply using the *predict* function of the bnlearn package.

Scenarios were used to select a subset, S^*, for which the standardized difference between the predicted outcome and the current outcome was minimized

$$S^* = \left\{ (t, d, r) \,|\, (t, d, r) \in S, \frac{\left|\widehat{Y}_i - Y_i\right|}{\sigma} = \min \frac{\left|\widehat{Y}_i - Y_i\right|}{\sigma} \right\},$$

where $\widehat{Y}_i$ is the predicted outcome state (e.g., predicted diet affordability) for a scenario and an outcome, i, Y_i is the mean outcome state within the data (e.g., mean diet affordability for that country), and σ is the SD of the outcome state. This approach was used for the agricultural GHGe and diet affordability outcomes, as well. It was also used as the approach when selecting scenarios which minimize incidence of food insecurity; however, the outcome was a condensed reference, defined as the sum of individual standardized differences of the prevalence of anemia, the incidence of childhood disease, and the incidence of food insecurity. Finally, when defining a set of scenarios that jointly minimized each of the outcomes of interest, the target of the optimization was

$$S^* = \left\{ (t, d, r) \,|\, (t, d, r) \in S, \max_i \frac{\left|\widehat{Y}_i - Y_i\right|}{\sigma} = \min \max_i \frac{\left|\widehat{Y}_i - Y_i\right|}{\sigma} \right\}.$$

Although this joint optimization structure can appear counterintuitive, it works to ensure the outcome with the greatest standardized difference (i.e., furthest from the goal of minimization) is prioritized.

Sets of scenarios were identified as optimal in most optimization efforts because often many scenarios resulted in an equivalent predicted reduction in the outcome variable. This occurred primarily when a scenario outcome was independent of the variables adjusted in the scenario. For example, DEP were identified as conditionally independent of GHGe, thus scenarios where DEP were varied without changing RM had minimal estimated influence on GHGe. Another cause for sets of scenarios identified as optimal was due to outcome predictions that were bounded such that they could not exclude the maximum observed within the dataset and could not be less than 0. This bounding was to minimize avoidable error due to extrapolation outside the derivation data. Further, if no difference in an outcome was observed over the simulations (i.e., $\frac{\left|\widehat{Y}_i - Y_i\right|}{\sigma} = 0$ for all scenarios), the optimal ASF supply was assumed to remain at current levels.

Because each optimization resulted in a set of scenarios, rather than a single scenario, distribution of this set of optimal scenarios was evaluated to understand the median food supply scenario supporting optimal outcomes, as well as the food supply scenarios containing the minimum and maximum levels of total ASF. The median scenario was used because these scenarios were not normally distributed in terms of food supply.

Correlations. Aligned, raw data by country and year were used to develop a correlation matrix to assess directionality (sign) and significance of associations among variables. Pearson correlation coefficients were determined for relationships among per capita food category supplies, nutritional health and food security indicators, and socioeconomic factors using the 2017 FAO Stat database (9–14). The year 2017 was selected as that for which World Bank Data Bank: Food Prices for Nutrition (67) was available for describing the proportional share of cost of different food categories in a least-cost healthy diet by country. These data were regressed against the index for political stability from 2017 (12). Three nations which did not have data for 2017 (Bahrain, Bhutan, and Qatar) were excluded from this evaluation. Analyses were performed with the correlation and regression procedures, respectively, of SAS (Vers. 9.4, SAS Institute Inc., Cary, NC).

Limitations. Although analytical methods were selected to support more causal inference, fundamentally all assessments within this analysis are based on empirical correlations within the data and are not causal or mechanistic. A variable may serve as a proxy for others not included in the dataset that have impact. Relationships are subject to the validity and accuracy of the data and reflect variation in one variable that corresponds to variation in another. Covariation among factors, unmeasured sources of variation, and random alignment among food supplies may confound the relationships highlighted in the study. The data include spatial and temporal relationships that were not expressly accounted for, or may be incompletely accounted for, in the analysis. This autocorrelation has potential to bias the results, particularly when exploring specific country contexts. The results are also dependent on the assumptions used in analysis, which were driven by the objectives of the study. Much like the limitations of epidemiological assessments of diet and health outcomes, the analyses in this study primarily serve to raise questions to drive further studies seeking mechanisms and testing hypotheses.

Data, Materials, and Software Availability. Data underlying this manuscript are made accessible through the Virginia Tech Data Repository at https://doi.org/10.7294/27089158 (68). Previously published data were used for this work (https://www.fao.org/faostat/en/) (9–14).

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