ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
10 September 2021

REVISED
24 November 2021

ACCEPTED FOR PUBLICATION
6 December 2021

PUBLISHED
30 December 2021

LETTER

Historical food consumption declines and the role of alternative foods

Danielle M Ferraro[1,2,3,4], Richard S Cottrell[1], Gordon D Blasco[1], Halley E Froehlich[5,6] and Benjamin S Halpern[1,2]

1 National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, CA, 93101, United States of America
2 Bren School for Environmental Science and Management, University of California, Santa Barbara, CA, 93106, United States of America
3 Environmental Markets Lab, University of California, Santa Barbara, CA, 93106, United States of America
4 Marine Science Institute, University of California, Santa Barbara, CA, 93106, United States of America
5 Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, CA, 93106, United States of America
6 Environmental Studies, University of California, Santa Barbara, CA, 93106, United States of America

E-mail: dferraro@ucsb.edu

Keywords: dietary change, food systems, food balance, supply, consumption, sustainability

Supplementary material for this article is available online

Abstract

The adoption of sustainable alternative foods could potentially reduce the environmental burden of human food production if it can reduce demand for products with higher environmental impact. However, there is little empirical evidence for how frequent food consumption declines are when alternative foods are introduced, limiting our knowledge of the potential for such introductions to drive food system transformations. Using 53 years of food supply data for 99 crop, livestock, and seafood commodities in 159 countries, we use regression analyses on 12 883 time series—each representing a single country-commodity pair—to detect sustained declines in apparent national food consumption, as well as corresponding consumption increases of other food commodities. First, we show that sustained declines in the consumption of any food item are rare, occurring in 9.6% of time series. Where declines are present, they most frequently occur in traditional plant-based staples, e.g. starchy roots, and are larger compared to animal-source foods, particularly in low- and middle-income countries where much of the future increase in food demand is expected to occur. Second, although declines were rare, we found national production rather than trade was identified as the most common proximate driver of declines in consumption, suggesting that shifts in diets have the potential to translate into reduced environmental impacts from food production. Third, we found consumption increases were nearly twice as common as declines, but only 8% of declines (from within 4% of total time series) occurred parallel to incline events within the same food group, suggesting limited interchangeability. An examination of case studies suggests that alternative foods can facilitate food system transitions, but strong relative disadvantages for existing foods across aspects of technology, markets, policy and culture need to exist in parallel to support for alternative foods across the same factors. Where existing foods are already produced in highly efficient systems, a lack of systematic disadvantage may provide a barrier to alternative foods driving change.

1. Introduction

The production of food is a major contributor to environmental degradation at a global scale [1, 2]. Food systems contribute between one quarter to a 3rd of current greenhouse gas emissions [3], appropriate nearly 40% of Earth's terrestrial surface [4], use more than 70% of available freshwater [5], and create substantial nutrient pollution [6, 7]. The net environmental impact (herein 'impact') of food production systems is of increasing concern as the challenge of sustainably feeding a growing population is coupled with increasing affluence and consumption of high-impact animal-source foods [8–12].

While various production and value-chain interventions will likely continue to increase the efficiency of the most resource-intensive foods, inescapable differences in production impacts among products are likely to persist [13, 14]. Therefore, shifting diets towards greater consumption of low impact alternative foods and sending market signals that disincentivize production of high-impact foods is widely considered a key strategy for reducing environmental damage from food and to avoid tipping points in natural systems [1, 8, 15–19].

Potential mechanisms for changing consumers' diets span policy interventions that shape regulatory or fiscal frameworks relating to food production and consumption, e.g. food carbon taxes [20, 21], and actions that target consumer choice either passively, e.g. structural nudges of consumer selection towards low-impact foods or the adoption of institutional food procurement policies that make low-impact foods more available [22–24] or actively, e.g. information and/or education campaigns, and ecolabeling [25, 26]. One largely consumer-driven, market-based approach to dietary change has been the development of low-impact food alternatives that provide consumers with a similar qualitative experience (e.g. taste, texture) as more resource-intensive or impact-prone products. Alternative foods may include new products such as plant-based alternatives (e.g. almond milk, veggie burgers), novel products (e.g. mycoproteins or cell-based foods), certified commodities (e.g. dolphin safe tuna) or existing products that have gained popularity through time or have been introduced to a new area [27–32]. Many alternative foods have lower per unit impacts (e.g. greenhouse gas emissions, land-use) than the majority of animal source foods [27, 33]. Yet, shifts to lower-impact alternative foods can drive sustainable consumption only if the higher-impact foods they are intended to substitute for are effectively replaced in peoples' diets [34–36]. Indeed, without sufficient substitution of existing products, alternative foods—including those with potentially lower environmental burdens—have the potential to have negative or unintended environmental outcomes. Despite the importance of decreases in consumption of an existing food when alternative foods are introduced, there is a lack of empirical evidence of the occurrence, frequency, or context of such events.

To address this research gap, we use regression analyses to detect historical country-level sustained declines in food supply data for 99 crop, livestock, and seafood commodities to identify the frequency and distribution of decline events in the apparent consumption (herein 'consumption') of different food groups globally over a 53 year time period. We also assess any corresponding increases within and between a given country's commodity groups, as well as the primary covariates (i.e. production, imports, exports) of consumption trends. In doing so we ask:

(a) How often do declines in food consumption occur, and in which food groups and geographic regions are they observed?
(b) What are the proximate drivers of these declines in food consumption?
(c) Do increases in consumption of similar foods coincide with declines, suggesting a possible mechanism for dietary shifts?

We then complement our statistical analyses with a qualitative review of key case studies to better understand the potential mechanisms and ultimate drivers of declines in food consumption and the role of alternative foods in dietary transitions.

2. Methods

2.1. Food balance sheets (FBS)

We used food balance data from the United Nations Food and Agriculture Organization (FAO) FAOSTAT database [37] to extract annual national data on the production, imports, exports, and uses of food commodities. The foods recorded in FBSs are typically primary commodities, e.g. fruits, vegetables, and cereals, but also include some processed commodities, e.g. vegetable oils and butter. Data are sourced from nations' official statistics, and estimated or imputed where data are unavailable.

The FAO calculates an annual domestic supply quantity for each commodity by combining production and imports, subtracting exports, and adjusting for stock changes. From there, an annual per capita food supply quantity is generated by subtracting food used for feed and seed, and dividing by population. These measures of food supply represent the quantity of food that is available for human consumption, but may differ from actual quantities consumed [38]. Nonetheless, FBSs provide the best available representation of quantities of foods consumed on a global scale.

Per capita food supply data (kg capita^{-1} year^{-1}), which we use as a proxy for apparent consumption, were downloaded for all available country-commodity pairs from 1961–2013. Though FBSs were also available for 2014–2017, they were computed with a different methodology and different estimates of population, and were thus excluded from this analysis in order to minimize any possible discontinuity between the two periods. We only considered national time series of individual food commodities, excluding any data describing aggregated regions (e.g. Europe) or aggregated commodities (e.g. animal products). We also excluded countries that formed or dissolved at any point during the study period ($n = 24$), such as the Soviet Union and its successors, due to potential discontinuities between former countries and their successors, as well as Sudan (former) which underwent large boundary and population adjustments following secession of South Sudan in 2011. Our final

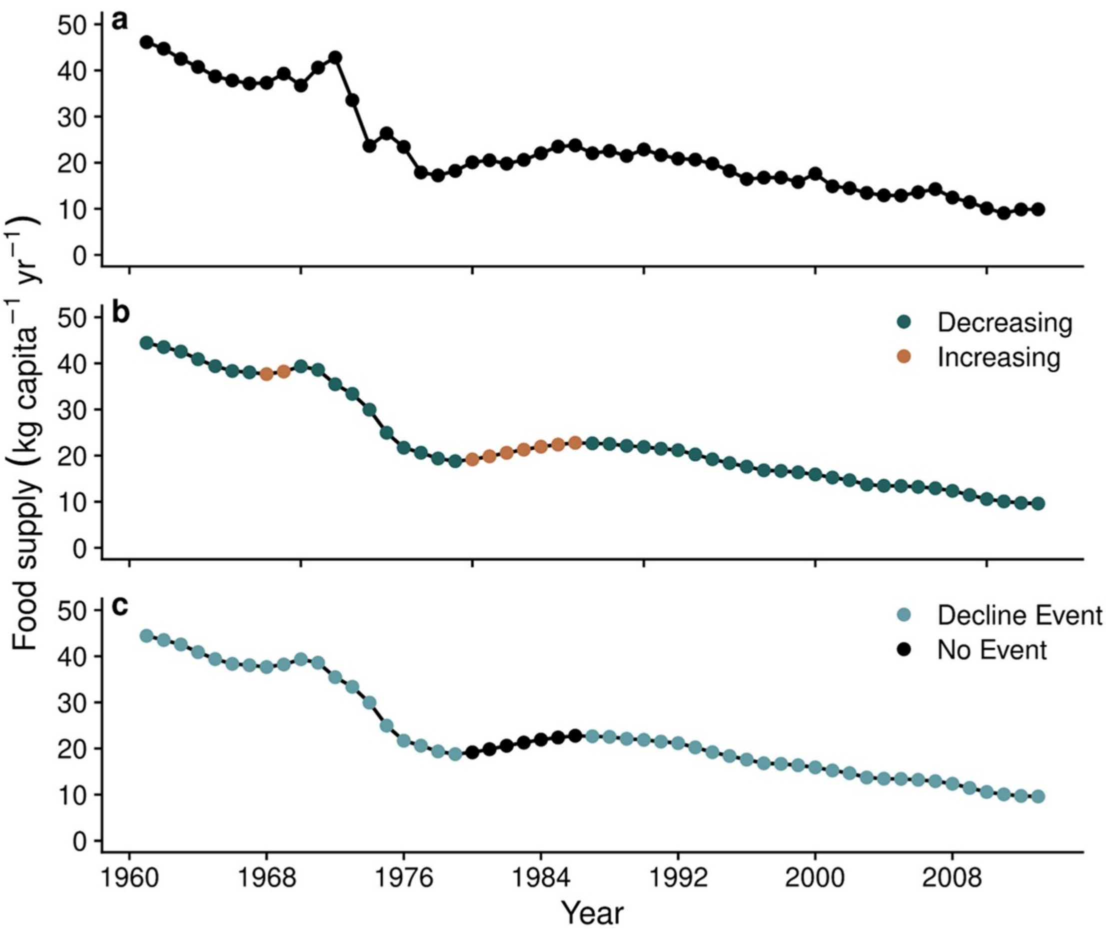

Figure 1. Method for identification of incline and decline events in food supply time series. The method is illustrated for Australia's mutton and goat meat commodity. (a) Raw per capita food supply (kg capita^{-1} year^{-1}) from 1961 to 2013. (b) Time series were smoothed with a 5 year rolling mean, then each year was characterized as increasing, decreasing, or stable by the slope of a 5 year rolling linear regression. (c) Consecutive years with the same trend were grouped together and defined as an event, and events of the same category were consolidated into a single event if they were less than 5 years apart. Finally, any event with a duration of fewer than 10 years was removed from the dataset.

set of food supply data consisted of 12 883 country-commodity time series from 159 distinct countries (table S1 (available online at stacks.iop.org/ERL/17/014020/mmedia)) and up to 99 distinct food commodities (table S2). Not every country had a supply time series for every commodity. Additionally, many novel foods, e.g. insects or mycoprotein, are not included in FBSs and thus could not be included in this analysis.

2.2. Event detection

To identify trends in apparent consumption of food commodities, we smoothed each time series with a 5 year rolling mean and computed slope over a 5 year rolling linear regression (figures 1(A) and (B)). Each year was classified as having an increasing, decreasing, or stable trend according to the sign of its slope. We effectively removed the stable slope class by assigning it only when the slope was exactly zero. Widening the range of slopes classified as stable, e.g. −0.05 to 0.05, interfered with the successful identification of decline and incline events as they were operationally defined for this work, according to visual inspection of the resulting event time series. Consecutive years with the same slope classification were grouped together and categorized as either an incline or decline event, depending on the slope classification (figure 1(C)). Finally, multiple events of the same category were consolidated into a single continuous event if there were less than 5 years between them. For every event, Mann–Kendall nonparametric trend tests were conducted to assess monotonic upward or downward trends. We used the 'trend' R package [39] to calculate the correlation coefficient Kendall's tau, which determined the strength and sign of the trend, as well as Sen's slope, which assessed the magnitude of the trend.

The resultant list of events was filtered to remove any event with a Kendall's tau value less than 0.6 or greater than −0.6, and a Sen's slope value less than 0.2 or greater than −0.2 for incline events and decline events, respectively. Kendall's tau thresholds were set to remove events with weak trends, and Sen's slope thresholds set to remove events with only minimal changes in supply quantity. Additionally, we removed any event <10 years in duration to isolate persistent trends in food supply. We tested a range of values for both parameters, and found them to be relatively robust to our choice (figure S1).

We calculated duration and absolute and proportional change in food supply for every event. We also assigned every food commodity one of ten food groups: alcoholic beverages; cereals and pulses; fruits and vegetables; meat and offals; milk, eggs, and animal fats; seafood; starchy roots; sugar and sugar crops; vegetable oils and oil crops; other. The 'other' category contains stimulants, spices, tree nuts, infant food, and commodities left unspecified, i.e. 'miscellaneous' (table S2). Additionally, FAO FBS metadata was used to pair each event to the geographic region and income group associated with its country. For every food group and geographic region, we calculated a proportional decline frequency defined as the number of decline events divided by the number of time series analyzed. We also calculated the proportional composition of food groups that made up the detected declines within each income group.

2.3. Event recovery

We classified each decline event as recovered or unrecovered by assessing if, at some point in the time series following the last year of the event, the food supply quantity recovered 95% of the quantity lost. We tested sensitivity of our results to a range of thresholds (75%, 80%, 85%, 90%, 95% and 100%) and found the proportion of recovered decline events was relatively insensitive to choice of threshold (figure S2).

2.4. Proximate driver correlative analysis

Food supply, here used as a proxy for consumption, is the residual of food production and utilization [38], such that changes in supply are fundamentally underpinned by changes in production, exports, imports, or some combination. Supply is also influenced by the diversion of biomass to animal feed or seed, stock changes (including governments, producers, retailers, exporters, and importers, among others), as well as supply chain waste.

To understand the proximate drivers of consumption declines, i.e. the elements of supply most associated with the declines we detect rather than the ultimate drivers affecting these elements in turn, we conducted parallel pairwise correlations of production, imports and exports with supply (figure S3). We excluded all other elements of supply because production and trade are the main processes by which food is made available to consumers, and we were fundamentally interested in whether consumption changes were most closely associated with domestic production or international sourcing. We removed decline events that were missing associated production, imports, and exports data and we converted all elements to per capita quantities (kg capita^{-1} year^{-1}). For our correlative analysis, any element with an absolute value of Spearman's rho greater than or equal to 0.9 was classified as a dominant correlate. This threshold was chosen to highlight only the strongest correlates; we tested sensitivity of results to different thresholds (0.5, 0.6, 0.7, 0.8, and 0.9) and found results robust to the threshold (figure S4). If no element had a rho value that exceeded 0.9, the element with the largest rho value was classified as the dominant correlate for that supply decline. We summarized frequency and percentage of declines associated with different dominant correlates in total and across each food group. For all declines with per capita production as a dominant correlate, we also evaluated if absolute production decreased during the same time period by evaluating the sign of the coefficient of a linear model fit to the production time series. We used the same method to analyze changes in harvestable area and yield during the decline period for crop commodities.

2.5. Identification of coinciding events

If an increase in consumption of one food was causally linked to declining consumption of another food, the respective increases and decreases in food supplies should overlap temporally. To detect which decline events occurred near the same time as incline events of different foods in the same country, we developed a method to identify coinciding pairs of incline and decline events. First, events had to occur in the same country and begin within ± 2 years of each other; this constraint bound events to only those within a close temporal distance from each other in order to mimic our hypothesized conditions of a strong causal interaction between two foods. Further, many pairings were likely correlative, so this constraint also limited the resulting number of paired events. Incline events were allowed to precede or follow decline events, since the introduction of an alternative food could lead to a pronounced decline in the supply of an existing food already experiencing minimal supply losses. This approach provided a buffer around the error associated with our method of detecting the start year of each event. We tested the sensitivity of this time window (1–5 years) and found that the resulting number of paired events was robust to the value chosen (figure S5). Second, the incline event had to have a maximum smoothed quantity within 50% of that of the decline event to prevent pairing of events with substantially different magnitudes of food supply. Finally, each coinciding event pair was classified as an intra-group or inter-group pair, depending on whether the two food commodities were part of the same or different food groups, respectively, based on our grouping of FBS metadata (table S2).

2.6. Case study selection and approach

We used case study analysis to understand the role of food introductions on declining consumption of others, beyond coinciding trends we identify. We overlaid coinciding decline and incline events graphically to highlight strong correlative patterns within and among food groups. We then paired this exploratory process with our knowledge of documented changes in global food consumption patterns, such as widespread declines in starchy root consumption and increased consumption of animal-based foods [40] to identify a range of case study candidates. Guided by proximal driver analyses for each example (i.e. whether supply inclines/declines were most associated with production, trade, etc), we searched Google Scholar and Web of Knowledge databases for relevant peer-reviewed literature that focused on ultimate drivers of food system transitions for those cases, i.e. the social, economic, and/or environmental factors underpinning changes in production, trade, or otherwise. We selected final case studies that were compelling examples of where food introductions contributed to the decline of others across a range of food groups. Where multiple, simultaneous declines of the same food group, e.g. various seafood commodities, were found in the same country, we aggregated those declines together to match the resolution those trends were reported at in the literature.

All data processing and analysis was performed using R version 4.0.2 [41] using the following packages: broom [42], cowplot [43], here [44], ggdist [45], ggpubr [46], janitor [47], paletteer [48], patchwork [49], png [50], readxl [51], rnaturalearth [52], scatterpie [53], sf [54], slider [55], tidyverse [56], trend [39], vroom [57].

3. Results and discussion

3.1. Frequency and distribution of declines in food supply

From the 12 883 country-commodity time series analyzed, we identified only 1689 individual decline events (from within 12% of time series) over the 53 year period (table S3). Typically, a time series only contained a single decline event if any were detected, though 10% ($n = 164$) of these time series with declines contained a 2nd decline event (e.g. figure 1) and <1% ($n = 6$) contained a 3rd. Of the decline events detected, 20% ($n = 344$) later recovered at least 95% of the lost supply quantity (figure S2). Our results herein describe the remaining 1345 decline events (from within 9.6% of time series) that did not recover (figure 2).

These unrecovered declines in food supply were relatively uncommon, with an overall frequency of 0.10, where frequency was defined as the number of decline events divided by the number of time series analyzed (figure 2). However, frequencies of decline events were variable across food groups, with the highest decline frequency found in the starchy roots food group (0.27), followed by alcoholic beverages (0.18) and cereals and pulses (0.18). Lowest decline frequencies occurred for seafood (0.07), vegetable oils and oil crops (0.03), and 'other' (0.01) food groups. Indeed, sustained declines in food supply tended to be far more common in plant-based products than for animal-source foods.

Decline trends varied across countries, but clear patterns emerged in the composition of food groups that experienced supply declines when countries were aggregated by income group (figure 3). The highest frequencies of food supply declines (0.16–0.20) occurred in Northern America, Australia and New Zealand, Melanesia, Micronesia, and Polynesia. The lowest decline frequencies (<0.07) occurred in Southern Asia and Northern Africa. Collectively, the majority of decline events found in low or middle income countries were in crop commodities (e.g. starchy roots, cereals, pulses, fruits and vegetables), aligning with the pattern of reduced dependence on traditional staples and increased preference for animal products and consistent with consumers becoming more affluent and urbanized [10, 40, 58]. In contrast, high income countries had higher proportions of declines in animal-source foods like meat, seafood, eggs, and dairy products. These patterns would seem to support an environmental Kuznets curve, where consumers eat increasingly more animal-based products as a country develops, but deliberately reduce their consumption after a certain threshold of income as awareness grows of environmental, health, and animal rights implications of food production and consumption [59, 60]. Contrary to trends in other animal products, seafood supply declines were relatively infrequent across all regions, likely due to a combination of near ubiquitous growth in global fish consumption over the last 60 years [61], and a portfolio of thousands of wild-caught and farmed species produced domestically and traded that buffer patterns of decline.

We found disparities in the magnitude of declines across these groups. For instance, while declines in meat, eggs, and dairy supplies dominate the overall number of food supply declines in high income countries, the proportional reduction in apparent consumption of these products is smaller than that of crop-based commodities in low and middle income countries. In particular, declines in starchy roots in low and middle income countries have an average loss of 65%, while declines in meat, eggs, and dairy products in high income countries have an average loss of 40% (figure S6). Thus, where reductions in apparent consumption of animal-based foods are occurring, these changes may be less significant compared to areas where plant-based foods are being replaced in diets. In addition to these relatively small declines in high income countries, it has been estimated that decreasing rates in meat consumption may not occur until per capita incomes reach equivalents of between USD $36–$50 thousand [59]. The ever rising ceiling of per capita demands from a large proportion of the world's growing human population, and such a distant inflection point for most countries,

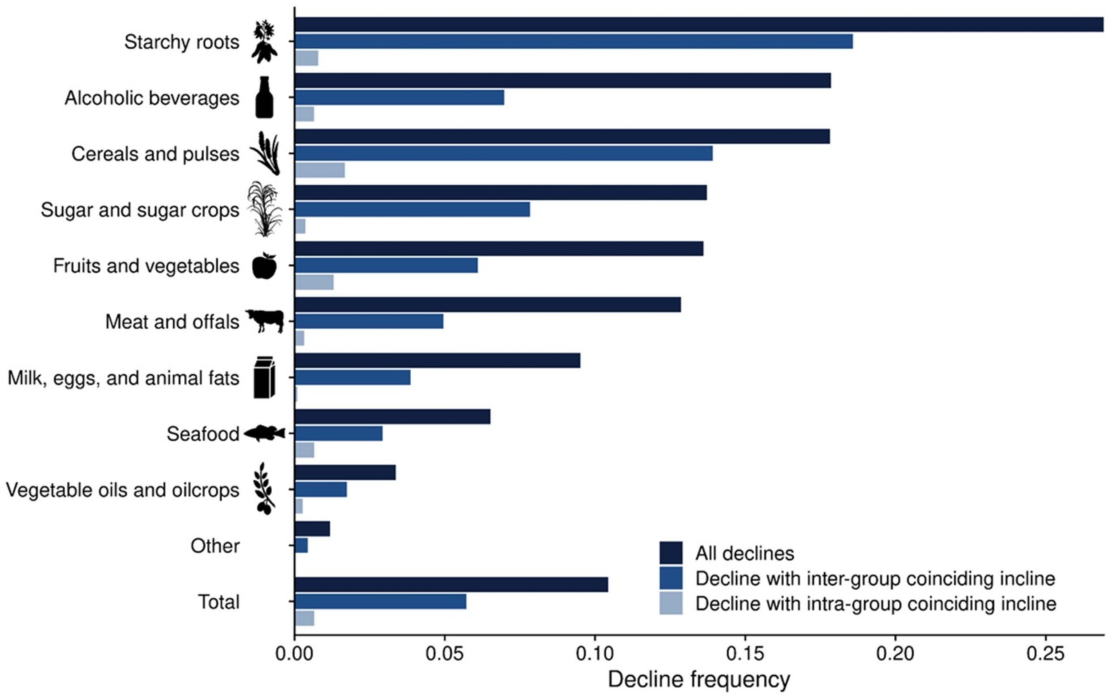

Figure 2. Proportional frequency of unrecovered supply declines in each food group. Proportional frequency was calculated as the number of decline events divided by the number of time series analyzed per food group. Bars are colored to represent decline events without a coinciding incline, with a coinciding incline of a different food group, and with a coinciding incline of the same food group.

highlights the enormity of the challenge to reduce the environmental burden from human food demands.

The median decline duration was 16 years, and ranged from 10 years (our minimum threshold) to 53 years (the length of the FBS time series). Because duration is conditional on the 1st year of the detected decline and limited by the length of the FBS time series, its contribution to the overall characterization of the declines detected is minimal.

3.2. Proximate drivers of declines in food supply

Of the 1345 unrecovered decline events we detected, 25 had missing or no non-zero production, imports, and exports data and were removed from the proximate driver analysis, leaving 1320 declines remaining. Per capita production was most strongly correlated with per capita food supply, with a median Spearman's rho value of 0.91 (figure 4(a)). It was also the element of supply most frequently categorized as a dominant correlate, associated with 62% (n = 842) of all food supply declines, followed by imports (27%, n = 368), and exports (11%, n = 148) (figure 4(b)). Within food groups, per capita production remained the most common proximate driver of supply declines, followed by per capita imports (figure 4(c)). In all food groups, exports were a dominant correlate for only a small percentage of supply declines, but played the largest role for sugar and sugar crops as the proximate driver of 20% of supply declines within that food group.

Positive dietary changes towards more sustainable consumption do not necessarily result in environmental benefits as the complex relationships among factors such as product substitutability, market dynamics, trade relationships, and the relative environmental impacts of all foods in the dietary profile may diminish or completely prevent the intended environmental outcome [34–36]. Yet, the prominence of a country's domestic production as the dominant driver of the same country's food supply declines suggests local dietary shifts through policy and consumer behavior may be able to reduce impacts of food production domestically for many food items. That said, addressing overexploitation by trading countries is still pertinent, especially wealthier nations importing seafood and oil crops, where trade rivals that of domestic production's influence on declines [37, 62]. Additionally, while all supply elements in our analyses are per capita transformations (and so plausibly decreasing per capita production could just mean population is outpacing production), in 85% of the declines with production as the dominant driver, absolute production also declined. Further, for 39% of production-driven declines in crop products, harvestable area also declined while yield remained constant or increased for the majority of cases. Understanding realized impact reduction from production changes is complicated given the uncertainty over resulting changes to land or water body management practices, system-specific

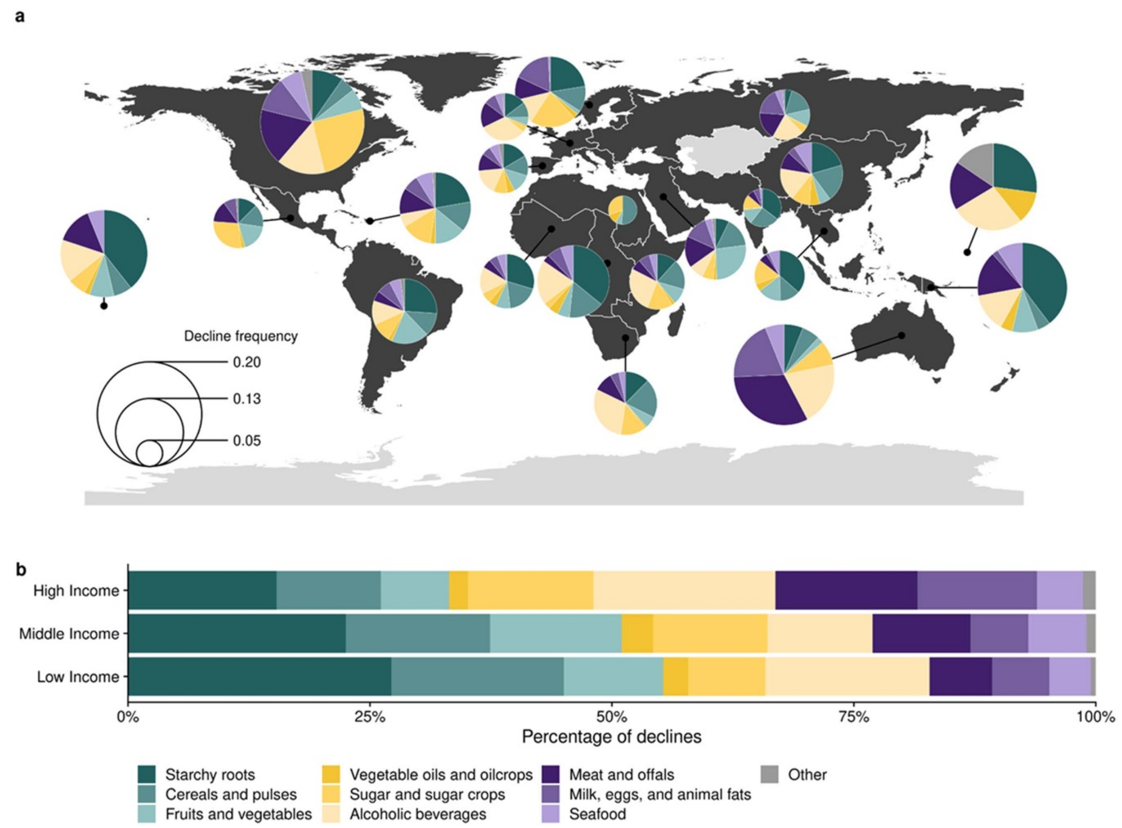

Figure 3. Distribution of unrecovered food supply decline events geographically and within economic groups. (a) Decline frequencies per geographic region and the respective composition of food groups therein. Pie chart and pie section size is scaled to the normalized decline frequency within each region and food group. Regions include Australia and New Zealand, the Caribbean, Central America, Eastern Africa, Eastern Asia, Eastern Europe, Melanesia, Micronesia, Middle Africa, Northern Africa, Northern America, Northern Europe, Polynesia, South America, South-Eastern Asia, Southern Africa, Southern Asia, Southern Europe, Western Africa, Western Asia, and Western Europe. Regions in light gray, i.e. Antarctica and Central Asia, were omitted from analysis due to lacking or insufficient data. (b) Proportional composition of decline event food groups within economic groups. Percentages represent normalized decline frequencies within each income group and food group.

sensitivity to intensification (e.g. increased fertilizer application) and the multifaceted, cumulative nature of food production impacts [11, 13, 63]. Additionally, production decreases may occur simultaneously with increased imports, which can produce uncertain sustainability outcomes as the environmental burdens associated with food type, production method, transportation mode and distance, and other factors along the supply chain are complex [64, 65]. Nonetheless, the importance of dietary change fundamentally depends on the assumption that with the reduction in demand for certain foods, reduced environmental pressures from production will ensue.

3.3. Exploring the role of alternative foods in consumption declines

Implicit in the idea of substituting foods to improve sustainability is the assumption that they will reduce demand for existing, less sustainable foods, yet we found little evidence of closely coupled associations from our analysis of coinciding inclines. In fact, consistent with trends of increasing per capita consumption, incline events were over twice as frequent as decline events, with a total incline frequency of 0.22 ($n = 2854$ incline events; table S4), and only a minority (30%, $n = 853$) coincided with unrecovered decline events (table S5). Overall, incline events preceded decline events as frequently as they followed them, with the incline preceding and following in 26% and 24% of paired coinciding events, respectively (figure S7(a)). There was some variation within food groups; for vegetable oils and oil crops as well as meat and offal declines, the coinciding incline generally preceded the decline. However, we note that the identification of the 1st year of an event, and subsequent implication of these results, is limited by the length of the time series in this study. Indeed, 50% of all coinciding incline and decline events began in the same year, solely because the overwhelming majority of those events began in the first year of the time series (figure S7(b)). Unrecovered decline events did not appear to coincide more frequently with incline events than recovered decline events did, with 40% of unrecovered declines matched to an incline versus 36% of recovered declines. Pairing of decline and incline events was more common (90% of all coinciding events) across different food groups (e.g. cereals and seafood), while only 8% of declines

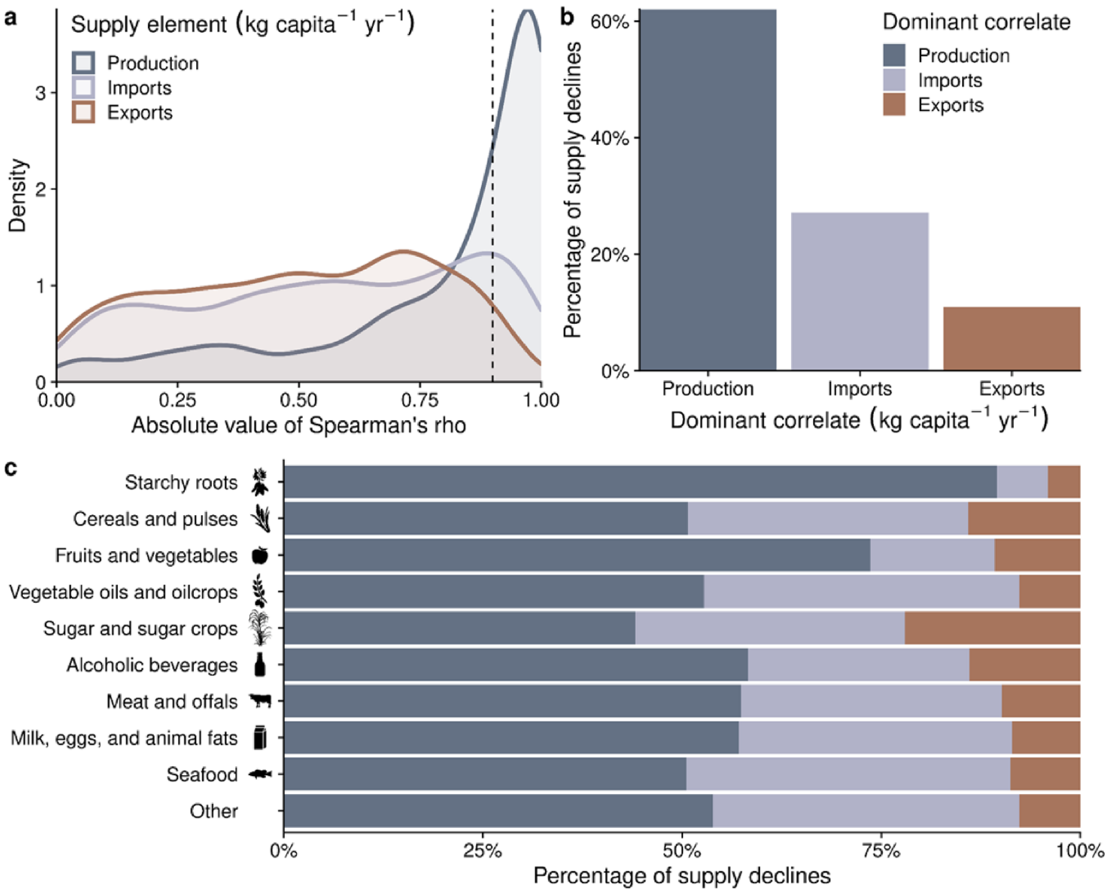

Figure 4. Dominant correlations between per capita food supply and utilization elements, i.e. per capita production, imports, and exports (kg capita^{-1} year^{-1}), during unrecovered supply declines. (a) Kernel density estimation (bandwidth = 0.05) of the absolute value of correlation coefficients (Spearman's rho) between per capita food supply and its constituent elements. Dashed line indicates a Spearman's rho value of 0.9. (b) Percentage of total supply declines where each constituent element of supply was determined to be a dominant correlate, where a dominant correlate was defined as an element with Spearman's rho $\geqslant$ 0.9, or the element(s) with the maximum Spearman's rho value in the case none exceeded rho $\geqslant$ 0.9. (c) The proportional distribution of dominant correlates within each food group.

occurred in tight association with incline of a food item within the same food group (e.g. meats, such as beef and chicken; figure S8). These intra-group event pairs were detected in fewer than 4% of all time series analyzed. Some inter-group pairs reveal associations between declines in higher-impact foods with inclines in foods with relatively lower impacts. For example, 46% of the declines in meat and offals that were paired with a coinciding incline were matched with inclines in crop commodities, namely cereals and pulses along with fruits and vegetables. In these cases, ultimate drivers underpinning consumption trends may be driving both the decline and incline, however our results suggest that if strong causal coupling between increase in one food and decline of another does exist, it is likely to be exceptionally rare.

Nonetheless, there have been well documented examples of where alternative foods have contributed to food system transitions across different economies and cultures. In Indonesia, starchy roots (cassava and sweet potato) have largely given way to cereals in diets (rice and, to a lesser extent, wheat); in Australia, poultry has overtaken beef and other red meats as the dominant source of animal protein; and in Japan, fish and seafood consumption has declined in contrast to global trends, with white meat (chicken/pork) increasingly consumed in its place (figure 5). Recent work highlights how the rise of new food depends on numerous facilitative conditions in science and technology, markets, state action or policy, and culture [26]. For example, the rapid rise of chicken in Japan was facilitated by increasing adoption of advances in breeding, husbandry and intensification which allowed dramatic increases in yields, historical marketing campaigns that associated the meat with military prowess, and a cheap source of animal protein following the Uruguay Round of the General Agreement on Trade and Tariffs in 1993 [26]. Similar trends are also evident in Indonesia, where the surge in rice production from the 1960s to 1990s was assisted by government investment in seed technologies, hybrids, and irrigation infrastructure, that rice consumption has a long standing history of consumption in the country, and wheat consumption greatly increased after trade restructuring following the 1997–98 financial crisis.

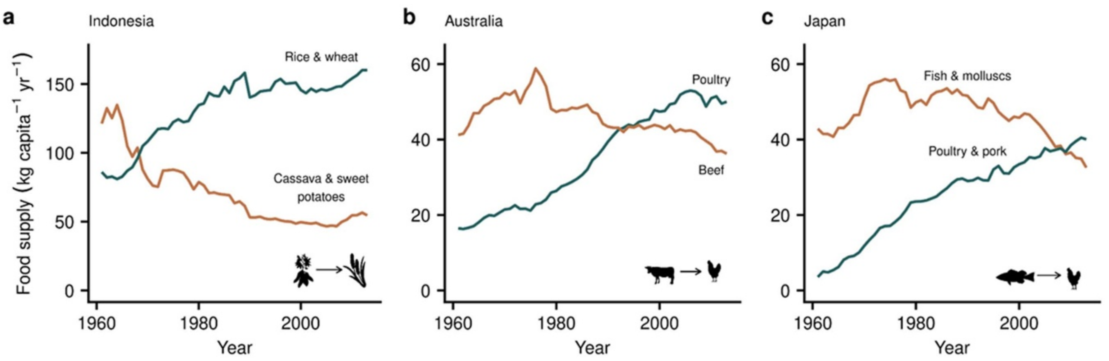

Figure 5. Case studies of known food transitions where alternative foods contributed to shifts in per capita consumption of other foods. (a) Indonesia's declining supply of cassava and sweet potatoes and increasing supply of rice and wheat. (b) Australia's declining supply of beef and increasing supply of poultry. (c) Japan's declining supply of fish and molluscs and increasing supply of poultry and pork.

Yet the catalyzing factors for the rise of emergent foods do not necessarily explain the decline in others. In each of these case studies, the strong relative disadvantage of existing foods across the four facilitative factors is pronounced. In Indonesia, while rice seed technologies expanded in the 1960s, cassava yields plateaued until the 1980s, and the sluggishness of production cycles increasingly deterred producers. After World War II, tapioca (granulated cassava root) export markets also fell away as European and US trade partners started favoring local starch industries, reducing domestic production incentives. Culture played a further role—many now associate cassava consumption with poverty because of its historical use as a food security crop [66, 67], do not feel it satiates them, and preferentially purchase rice even when it is more expensive [68]. In Australia, the growing price gap between expensive beef and cheaper chicken is an important driver of transition, but this price difference cannot be explained solely by improved efficiency in poultry production [69]. The important contrast is that cattle are grazed in environments far from slaughterhouses and retailers, and regularly exposed to droughts, wildfires, and floods in recent years—all culminating in long and complex value chains with far greater price instability [70].

In both Australia and Japan, as consumers work longer hours and require more convenient meals, red meat (Australia) and fish/seafood (Japan) have become less favored than chicken or pork by consumers due to lower versatility and greater preparation time requirements [69, 71]. In the case of Australia, retail outlets are also increasingly deterred by the high variation in product form and quality in beef compared to other meats [69]. Further, reducing red meat consumption is embedded in Australian dietary guidelines, compared to a recommended increase in poultry consumption [72]. These are important distinctions for the emergence of alternative foods if they are to support food system transitions—the alternative food cannot only be well supported across facets of technology, markets, state action, and culture—foods targeted for replacement will likely need significant disadvantages in one or more of these considerations.

3.4. Challenges and opportunities for alternative foods to drive more sustainable consumption

Meeting human food demand while reducing environmental impact will continue to be a grand challenge. The potential for shifts away from terrestrial meat consumption to benefit people and the planet has been well-demonstrated [1, 8, 9, 16, 17, 73], but we find consumption declines in these foods have been comparatively rare. Instead, foods tend to be additive, which is a cautionary note for alternative foods entering the market—effective substitution will likely be hindered by a rising ceiling of per capita consumption [36, 74]. Commodities being developed to displace animal-source foods are often most available in high income countries where declines in animal-source foods already appear to be happening, a trend which may be able to be leveraged. However, cost, distribution constraints, and receptive markets create massive uncertainty to their ability to displace high-impact foods. The capacity for displacement may also be challenged by consumers' cultural, behavioral, or personal barriers to acceptance of alternative foods, e.g. neophobia or disgust, particularly in response to novel foods with ingredients or a production type unfamiliar to consumers [75]. In addition, new foods run the risk of displacing already low-impact foods depending on who adopts the product, e.g. pulses being absorbed into vegetarian markets rather than being consumed by meat consumers.

Even if alternative foods do displace their intended counterpart, evaluating whether or not these products are actually more sustainable is a complex endeavor. Sustainability assessments are often heavily biased towards comparisons of greenhouse gas emissions [76], but understanding the environmental performance of of these alternative foods will require evaluation over multiple metrics (e.g. land use, freshwater use, nutrient pollution) and ideally be spatially explicit given that impact is context-dependent [63]. This is especially true for highly traded commodities such as seafood and oil products. Thus, more holistic food policy will be increasingly important, especially given how the successful adoption of alternative foods has coincided with state actions that supported and incentivized growth in a particular food (e.g. rice and wheat in Indonesia). From infrastructure and distribution, to the underlying technology, actions to displace higher-impact foods will be more successful if efforts at the policy, industry, and consumer level align.

Our examination of case studies reveals how state policies can incentivize production of an alternative food and foster an increase in its consumption. Importantly, government intervention could also support the consumption of an existing, high-impact food via actions that keep supplies high, maintain affordable prices, and/or support distribution, which in turn could obscure co-occurring shifts in consumer demand towards lower-impact foods. For example, dairy producers in the United States have benefitted for decades from major government programs aiming to increase dairy income by purchasing excess supply, among other subsidies [77]. These actions are in contrast to recent trends in per capita milk consumption, which has been decreasing steadily while interest in alternative products, such as plant-based milks, has been on the rise [78, 79]. Yet, subsidies to support dairy income persist, and milk production continues to see steady growth [78]. In this way, government interventions have the potential to mask market signals from changes in consumer demand towards lower-impact foods, highlighting the strong influence of food policy on how increased consumption of alternative foods translates to changes in existing foods.

Data quality and resolution impact the ability to detect and understand food system dynamics. The accuracy of FBSs is first dependent on the accuracy and availability of the underlying measures of food production, utilization, and population. Since food supply is estimated by the FAO as a residual of these statistics, the accuracy of food supply data is contingent on the accuracy of their constituent components. Furthermore, food supply describes the quantity of food available for human consumption, but does not necessarily reflect the amount of food actually consumed. When compared with individual dietary surveys, FBSs tend to overestimate consumption [80, 81]. However, FBSs are the best available source of standardized data at a global scale that allows for comparisons of food consumption patterns over time.

Relatedly, data resolution precludes evaluation of more granular food items, arguably at the level consumer decisions occur. For instance, seafood products in FBSs are grouped into one of five commodities that represent thousands of fished and farmed species [82]. Such aggregation likely results in a 'portfolio effect' reducing the number of detected declines and limiting our ability to detect potential displacement between individual communities or species. And while the resolution of FBSs was sufficient for our analysis of larger, global food supply trends, downscaling to a given region and greater discernment of commodities may be more prudent for policy makers and consumers depending on the goal [63]. Lastly, some data categories are not directly comparable given the data structure. For example, demand for plant-based dairy alternatives has increased, but are embedded within the raw commodities from which they are composed (e.g. soybeans, tree nuts, or oats), not a separate 'milk' category. Thus, identifying interactions between such commodities are indiscernible in this dataset, and would require reclassifying and/or creating new categories.

4. Conclusion

The substitution of sustainable foods for other, higher-impact foods holds great promise for reducing the environmental burdens imposed by existing food systems. Yet, we found little empirical evidence for past reductions in the consumption of foods when alternative foods are introduced, suggesting that alternative foods are unlikely to be a widespread mechanism for food system transitions. While infrequent overall, an examination of the consumption declines that did occur showed that events tended to co-occur with losses in both absolute and per capita domestic production, indicating that dietary change has the potential to influence local impacts of a country's food production. Ideal cases for dietary change via alternative foods will have facilitative conditions to assist alternative food adoption, as well as strong disadvantages present for the existing food.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/danielleferraro/food-declines.

Acknowledgments

We are grateful to Heather Lahr for project management, and Jason Maier for discussions that helped shape the trajectory of this research. Icons were downloaded from the Integration and Application Network (credit Tracey Saxby, https://ian.umces.edu/media-library) and from https://flaticon.com (credit Freepik).

Funding

This work was funded by the National Philanthropic Trust.

ORCID iDs

Danielle M Ferraro https://orcid.org/0000-0003-3680-3545
Richard S Cottrell https://orcid.org/0000-0002-6499-7503
Halley E Froehlich https://orcid.org/0000-0001-7322-1523
Benjamin S Halpern https://orcid.org/0000-0001-8844-2302

References

[1] Willett W *et al* 2019 Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems *Lancet* **393** 447–92
[2] Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger W H, Simberloff D and Swackhamer D 2001 Forecasting agriculturally driven global environmental change *Science* **292** 281–4
[3] Burney J A, Davis S J and Lobell D B 2010 Greenhouse gas mitigation by agricultural intensification *Proc. Natl Acad. Sci. USA* **107** 12052–7
[4] Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42
[5] FAO 2011 *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) - Managing systems at risk* (Rome: Food and Agriculture Organization of the United Nations)
[6] Maxwell S L, Fuller R A, Brooks T M and Watson J E M 2016 Biodiversity: the ravages of guns, nets and bulldozers *Nat. News* **536** 143–5
[7] Campbell B, Beare D, Bennett E, Hall-Spencer J, Ingram J, Jaramillo F, Ortiz R, Ramankutty N, Sayer J A and Shindell D 2017 Agriculture production as a major driver of the Earth system exceeding planetary boundaries *Ecol. Soc.* **22** 8
[8] Tilman D and Clark M 2014 Global diets link environmental sustainability and human health *Nature* **515** 518–22
[9] Clark M A, Springmann M, Hill J and Tilman D 2019 Multiple health and environmental impacts of foods *Proc. Natl Acad. Sci. USA* **116** 23357–62
[10] Kearney J 2010 Food consumption trends and drivers *Phil. Trans. R. Soc.* B **365** 2793–807
[11] Hilborn R, Banobi J, Hall S J, Pucylowski T and Walsworth T E 2018 The environmental cost of animal source foods *Front. Ecol. Environ.* **16** 329–35
[12] Bajželj B, Richards K S, Allwood J M, Smith P, Dennis J S, Curmi E and Gilligan C A 2014 Importance of food-demand management for climate mitigation *Nat. Clim. Change* **4** 924–9
[13] Poore J and Nemecek T 2018 Reducing food's environmental impacts through producers and consumers *Science* **360** 987–92
[14] Herrero M and Thornton P K 2013 Livestock and global change: emerging issues for sustainable food systems *Proc. Natl Acad. Sci. USA* **110** 20878–81
[15] Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M and Toulmin C 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–8
[16] Springmann M *et al* 2018 Options for keeping the food system within environmental limits *Nature* **562** 519–25
[17] Clark M A, Domingo N G G, Colgan K, Thakrar S K, Tilman D, Lynch J, Azevedo I L and Hill J D 2020 Global food system emissions could preclude achieving the 1.5 °C and 2 °C climate change targets *Science* **370** 705–8
[18] Kim B F *et al* 2020 Country-specific dietary shifts to mitigate climate and water crises *Glob. Environ. Change* **62** 101926
[19] Ivanova D, Barrett J, Wiedenhofer D, Macura B, Callaghan M and Creutzig F 2020 Quantifying the potential for climate change mitigation of consumption options *Environ. Res. Lett.* **15** 093001
[20] Garnett T, Mathewson S, Angelides P and Borthwick F 2015 Policies and actions to shift eating patterns: what works?: a review of the evidence of the effectiveness of interventions aimed at shifting diets in more sustainable and healthy directions (Chatham House) (available at: www.research.ed.ac.uk/en/publications/policies-and-actions-to-shift-eating-patterns-what-works-a-review) (Accessed 20 May 2021)
[21] Dogbe W and Gil J M 2018 Effectiveness of a carbon tax to promote a climate-friendly food consumption *Food Policy* **79** 235–46
[22] Garnett E E, Marteau T M, Sandbrook C, Pilling M A and Balmford A 2020 Order of meals at the counter and distance between options affect student cafeteria vegetarian sales *Nat. Food* **1** 485–8
[23] Byerly H, Balmford A, Ferraro P J, Wagner C H, Palchak E, Polasky S, Ricketts T H, Schwartz A J and Fisher B 2018 Nudging pro-environmental behavior: evidence and opportunities *Front. Ecol. Environ.* **16** 159–68
[24] Fitch C and Santo R 2016 Instituting change: an overview of institutional food procurement and recommendations for improvement (Baltimore, MD: The Johns Hopkins Center for a Livable Future) (available at: https://clf.jhsph.edu/publications/instituting-change-overview-institutional-food-procurement-and-recommendations) (Accessed 11 November 2021)
[25] Wojnarowska M, Sołtysik M and Prusak A 2021 Impact of eco-labelling on the implementation of sustainable production and consumption *Environ. Impact. Assess. Rev.* **86** 106505
[26] Moberg E *et al* 2021 Combined innovations in public policy, the private sector and culture can drive sustainability transitions in food systems *Nat. Food* **2** 1–9
[27] Parodi A *et al* 2018 The potential of future foods for sustainable and healthy diets *Nat. Sustain.* **1** 782–9
[28] McClements D J, Newman E and McClements I F 2019 Plant-based milks: a review of the science underpinning their design, fabrication, and performance *Compr. Rev. Food Sci. Food Saf.* **18** 2047–67
[29] Slade P 2018 If you build it, will they eat it? Consumer preferences for plant-based and cultured meat burgers *Appetite* **125** 428–37
[30] Hashempour-Baltork F, Khosravi-Darani K, Hosseini H, Farshi P and Reihani S F S 2020 Mycoproteins as safe meat substitutes *J. Clean. Prod.* **253** 119958
[31] Leadbitter D and Benguerel R 2014 Sustainable tuna—can the marketplace improve fishery management? *Bus. Strategy Environ.* **23** 417–32
[32] Jallinoja P, Niva M and Latvala T 2016 Future of sustainable eating? Examining the potential for expanding bean eating in a meat-eating culture *Futures* **83** 4–14
[33] Smetana S, Mathys A, Knoch A and Heinz V 2015 Meat alternatives: life cycle assessment of most known meat substitutes *Int. J. Life Cycle Assess.* **20** 1254–67
[34] Farmery A K, Putten I E V, Phillipov M and McIlgorm A 2020 Are media messages to consume more under-utilized seafood species reliable? *Fish Fish.* **21** 844–55
[35] Halpern B S *et al* 2021 The long and narrow path for novel cell-based seafood to reduce fishing pressure for marine ecosystem recovery *Fish Fish.* **00** 1–13
[36] Cottrell R S, Maier J, Ferraro D M, Blasco G D, Geyer R, Froehlich H E and Halpern B S 2021 The overlooked importance of food disadoption for the environmental sustainability of new foods *Environ. Res. Lett.* **16** 104022

[37] FAO 2020 Food balances (old methodology and population) (Food and Agricultural Organization of the United Nations) (available at: www.fao.org/faostat/en/#data/FBSH (Retrieved 24 September 2019))
[38] FAO 2001 Food balance sheets: a handbook (Food and Agricultural Organization of the United Nations) (available at: www.fao.org/3/x9892e/X9892E00.htm (Accessed 19 January 2021))
[39] Pohlert T 2020 Trend: non-parametric trend tests and change-point detection (available at: https://CRAN.R-project.org/package=trend (Retrieved 06 May 2020))
[40] Kastner T, Rivas M J I, Koch W and Nonhebel S 2012 Global changes in diets and the consequences for land requirements for food *Proc. Natl Acad. Sci. USA* **109** 6868–72
[41] R Core Team 2020 *R: A Language and Environment for Statistical Computing* (Vienna: R Foundation for Statistical Computing)
[42] Robinson D, Hayes A and Couch S 2021 Broom: convert statistical objects into tidy tibbles (available at: https://CRAN.R-project.org/package=broom (Retrieved 01 January 2021))
[43] Wilke C O 2020 Cowplot: streamlined plot theme and plot annotations for "ggplot2" (available at: https://CRAN.R-project.org/package=cowplot (Retrieved 06 May 2020))
[44] Müller K 2020 Here: a simpler way to find your files (available at: https://CRAN.R-project.org/package=here (Retrieved 06 May 2020))
[45] Kay M 2021 ggdist: visualizations of distributions and uncertainty (available at: https://mjskay.github.io/ggdist/ (Retrieved 01 January 2021))
[46] Kassambara A 2020 ggpubr: "ggplot2" based publication ready plots (available at: https://CRAN.R-project.org/package=ggpubr (Retrieved 06 May 2020))
[47] Firke S 2021 Janitor: simple tools for examining and cleaning dirty data (available at: https://CRAN.R-project.org/package=janitor (Retrieved 01 January 2021))
[48] Hvitfeldt E 2020 Paletteer: comprehensive collection of color palettes (available at: https://CRAN.R-project.org/package=paletteer (Retrieved 06 May 2020))
[49] Pedersen T L 2020 Patchwork: the composer of plots (available at: https://CRAN.R-project.org/package=patchwork (Retrieved 06 May 2020))
[50] Urbanek S 2013 png: read and write PNG images (available at: https://CRAN.R-project.org/package=png (Retrieved 06 May 2020))
[51] Wickham H and Bryan J 2019 Readxl: read excel files (available at: https://CRAN.R-project.org/package=readxl (Retrieved 06 May 2020))
[52] South A 2017 rnaturalearth: World Map Data from Natural Earth (available at: https://CRAN.R-project.org/package=rnaturalearth (Retrieved 06 May 2020))
[53] Yu G 2019 Scatterpie: scatter pie plot (available at: https://CRAN.R-project.org/package=scatterpie (Retrieved 06 May 2020))
[54] Pebesma E 2018 Simple features for r: standardized support for spatial vector data *R J.* **10** 439–46
[55] Vaughan D 2020 Slider: sliding window functions (available at: https://CRAN.R-project.org/package=slider (Retrieved 06 May 2020))
[56] Wickham H *et al* 2019 Welcome to the tidyverse *J. Open Source Softw.* **4** 1686
[57] Hester J and Wickham H 2020 Vroom: read and write rectangular text data quickly (available at: https://CRAN.R-project.org/package=vroom (Retrieved 06 May 2020))
[58] Popkin B M 1993 Nutritional patterns and transitions *Popul. Dev. Rev.* **19** 138–57
[59] Cole J R and McCoskey S 2013 Does global meat consumption follow an environmental Kuznets curve? *Sustain.: Sci. Pract. Policy* **9** 26–36
[60] Vranken L, Avermaete T, Petalios D and Mathijs E 2014 Curbing global meat consumption: emerging evidence of a second nutrition transition *Environ. Sci. Policy* **39** 95–106
[61] FAO 2020 The state of world fisheries and aquaculture 2020 (FAO) (available at: www.fao.org/documents/card/en/c/ca9229en) (Accessed 23 September 2020)
[62] Watson R A, Nichols R, Lam V W Y and Sumaila U R 2017 Global seafood trade flows and developing economies: insights from linking trade and production *Mar. Policy* **82** 41–49
[63] Halpern B S *et al* 2019 Opinion: putting all foods on the same table: achieving sustainable food systems requires full accounting *Proc. Natl Acad. Sci. USA* **116** 18152–6
[64] Farmery A K, Gardner C, Green B S, Jennings S and Watson R A 2015 Domestic or imported? An assessment of carbon footprints and sustainability of seafood consumed in Australia *Environ. Sci. Policy* **54** 35–43
[65] Edwards-Jones G *et al* 2008 Testing the assertion that 'local food is best': the challenges of an evidence-based approach *Trends Food Sci. Technol.* **19** 265–74
[66] Dixon J 1979 Production and consumption of cassava in Indonesia *Bull. Indones. Econ. Stud.* **15** 83–106
[67] Boomgaard P 2003 In the shadow of rice: roots and tubers in Indonesian history, 1500–1950 *Agric. Hist.* **77** 582–610
[68] Hartini T N S, Padmawati R S, Lindholm L, Surjono A and Winkvist A 2005 The importance of eating rice: changing food habits among pregnant Indonesian women during the economic crisis *Soc. Sci. Med.* **61** 199–210
[69] Gatfield T 2006 Australia's gone chicken! *J. Food Prod. Mark.* **12** 29–43
[70] Australian Bureau Of Agricultural Resource Economics And Sciences (ABARES) 2019 Agricultural commodities: June quarter 2019 (available at: https://daff.ent.sirsidynix.net.au/client/en_AU/ABARES/search/detailnonmodal/ent: $002f$002fSD_ASSET$002f0$002fSD_ASSET:1027050/one) (Accessed 23 November 2021)
[71] Kitano S and Yamamoto N 2020 The role of consumer knowledge, experience,and heterogeneity in fish consumption: policy lessons from Japan *J. Retail. Consum. Serv.* **56** 102151
[72] National Health and Medical Research Council 2013 Australian dietary guidelines (Canberra) (available at: www.nhmrc.gov.au/guidelines-publications/n55 (Accessed 30 August 2021))
[73] Springmann M, Wiebe K, Mason-D'Croz D, Sulser T B, Rayner M and Scarborough P 2018 Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail *Lancet Planet. Health* **2** e451–61
[74] Cottrell R S, Ferraro D M, Blasco G D, Halpern B S and Froehlich H E 2021 The search for blue transitions in aquaculture-dominant countries *Fish Fish.* **00** 1–18
[75] Tuorila H and Hartmann C 2020 Consumer responses to novel and unfamiliar foods *Curr. Opin. Food Sci.* **33** 1–8
[76] Ridoutt B G, Hendrie G A and Noakes M 2017 Dietary strategies to reduce environmental impact: a critical review of the evidence base *Adv. Nutr.* **8** 933–46
[77] Frisvold G 2021 The US dairy industry in the 20th and 21st century *J. Food Law Policy* **16** 6
[78] USDA Economic Research Service 2021 Dairy data (available at: www.ers.usda.gov/data-products/dairy-data) (Accessed 14 November 2021)
[79] Sethi S, Tyagi S K and Anurag R K 2016 Plant-based milk alternatives an emerging segment of functional beverages: a review *J. Food Sci. Technol.* **53** 3408–23
[80] Serra-Majem L *et al* 2003 Comparative analysis of nutrition data from national, household, and individual levels: results from a WHO-CINDI collaborative project in Canada, Finland, Poland, and Spain *J. Epidemiol. Commun. Health* **57** 74–80
[81] Hawkesworth S, Dangour A D, Johnston D, Lock K, Poole N, Rushton J, Uauy R and Waage J 2010 Feeding the world healthily: the challenge of measuring the effects of agriculture on health *Phil. Trans. R. Soc.* B **365** 3083–97
[82] Blasco G D, Ferraro D M, Cottrell R S, Halpern B S and Froehlich H E 2020 Substantial gaps in the current fisheries data landscape *Front. Mar. Sci.* **7** 1088