PUBLIC HEALTH

Mixed diets can meet nutrient requirements with lower carbon footprints

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Achieving sustainable dietary change is essential for safeguarding human and environmental health. However, dietary recommendations based on broad food groups may not accurately reflect real-world realities because individuals select and consume dishes with multiple food items influenced by diverse context-specific factors. Therefore, here we explored the sustainability trade-offs of dietary choices at the dish level through an optimization modeling approach tested in Japan. We estimated the nutritional quality, price, and carbon footprint of major Japanese dishes and examined 16 dietary scenarios to identify options that meet the nutritional requirements and minimize carbon footprint. Overall, mixed diets contain more combinations of dishes that meet nutritional requirements with lower carbon footprints compared to more restrictive dietary scenarios. We argue that the approach developed here enables a better understanding of dietary trade-offs, complements existing methods, and helps identify sustainable diets by offering nuanced information at the national and sub-national levels.

INTRODUCTION

The need to feed the growing and increasingly affluent and urbanized global population has transformed radically food systems (*1*–*3*). Per projections by the Food and Agriculture Organization (FAO), feeding an estimated global population of 9.1 billion in 2050 would require a 70% increase in overall food production from 2005/2007 levels (*4*). At the same time, there is an urgent need to enhance the sustainability of food systems, as they are linked to multiple Sustainable Development Goals (SDGs) beyond SDG 2 (Zero Hunger) (*5*).

Diets are central elements of food systems (*6*), and thus, they affect sustainability in many ways (*7*). At the individual's level, insufficient or excessive food intake can be equally unhealthy, with malnutrition, micronutrient deficiencies, overweight, and obesity being major public health challenges (linked to SDG 3) in many countries worldwide (*8*, *9*). Simultaneously, catering for increasingly westernized diets relies on heavily industrialized agro-food production systems that substantially contribute to some of the most profound and challenging environmental problems (*10*), such as climate change, land use change, biodiversity loss, and poor water quality and scarcity (linked to SDG 6, 13, and 15) (*11*, *12*). For example, the agricultural sector is responsible for approximately 25% of greenhouse gasses (GHGs) emissions, especially through beef production (*13*), whereas food transport accounts for nearly 20% of the total emissions from food systems. Therefore, shifting to sustainable food production and consumption patterns is essential to avoid exceeding environmental limits (*14*–*16*) and ensuring planetary health (*7*). Diets are undeniably an important entry point to achieve these goals (*17*).

Efforts have been made to foster dietary transitions through behavioral change (*18*–*20*). Nearly 100 countries have developed dietary guidelines (*21*) to optimize the economic, environmental, and social aspects of diets. At the global level, the 2019 EAT-Lancet Commission proposed a healthy and sustainable diet that meets the needs of the growing global population through sustainable food systems, consisting predominantly of vegetables, fruits, nuts, and legumes while limiting the consumption of red meat and added sugars (*17*). It has been reported that diets limiting the intake of saturated fat and sodium while promoting the intake of protein and micronutrients may alleviate malnutrition (undernutrition and hyperalimentation) (*22*, *23*). However, the environmental implications tied to these dietary practices should also be considered.

Many studies have explored the complex relationship between diets and carbon footprint (*24*, *25*). However, the sustainability outcomes of current diets and future dietary transitions at different temporal and spatial scales have been explored mostly at the level of broad diet categories (e.g., vegetarian, pescatarian, and lacto-ovo-vegetarian) rather than at the dish level (*26*, *27*). Although scenario exercises using broad diet categories can help us understand high-level impacts and provide a general idea of how a healthy and sustainable diet can look like (*28*, *29*), they are also coarse. At the heart of this challenge is the reality that people do not consume the ingredients directly, but instead consume dishes made up of multiple ingredients and prepared with different cooking methods (*30*). This creates two problems: uncertainties in impacts and trade-offs estimation (*31*) and the inability to account for personal preferences and cultural sensibilities in food choices (*31*–*33*).

First, the difficulty of considering in broad diet scenarios important factors such as food processing characteristics (e.g., frozen and canned foods), food preparation methods, and minor ingredients, might lead to an underestimation of the environmental impact of diets (*34*). Furthermore, despite the rather robust and well-tested methodologies to estimate the nutrient content and the economic costs of individual dishes, it is much more complicated to estimate properly their carbon footprints. This is largely because the value chains of many food commodities may span many countries (*35*, *36*) with markedly different production methods and impacts for the same item (*37*–*39*). Studies assessing the carbon footprint of diets have increasingly considered impacts across entire supply chains, from production, transport, processing, and cooking (*30*, *40*, *41*), including inputs among different industries in the countries or regions from which food items originate (*42*). For example, environmentally extended input-output tables have been used to quantify the carbon footprint of diets in different sectors and regions (*43*–*46*), including in the United States (*47*), China (*48*, *49*), the European Union

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(*50–52*), and South Asia (*53*). Such consumption-based accounting methods can estimate the carbon footprint of diets and suggest appropriate options to promote low-carbon dietary transitions (*54–56*) but are yet to be mobilized effectively at the dish level.

Second, it is important to provide direct food intake recommendations at the individual's level (*17*, *57*). For example, certain individuals might prioritize the consumption of high-protein and low-calorie, low-salt, or low-cholesterol diets to prevent health problems, including obesity, and cardiovascular and other noncommunicable diseases (*58–62*). Furthermore, broad dietary scenarios can be implemented differently in different cultural contexts. A vegetarian or pescatarian diet can look very different between countries or world regions due to differences in the local availability or preferences for ingredients (*63*, *64*), and thus may have very different impacts (*16*, *18*, *65*, *66*). Arguably accounting for such differences in individual and cultural preferences could determine whether proposed dietary transitions are feasible in specific geographical contexts, and help estimate better the expected impacts (*67–69*).

Considering these realities, efforts have been made in recent years to develop more dish-specific approaches to understand the impact of diets (*70–72*). For example, environmental footprint analyses at the recipe level have provided insights into how using locally produced food could reduce carbon footprints (*71*) or how to create low-carbon meals in school canteens (*73*), among others. Furthermore, multiple online tools have been developed to calculate the carbon footprint of recipes (*70*, *74*). Similarly, although some aggregated scores have been utilized to explore the nutritional characteristics of diets at the dish level, such methods are still mostly linked to environmental impact metrics at the food group level or the broad diet level (*73*, *75*). Generally, such studies rely on secondary data from large-scale surveys containing diet recall modules at the dish level, which are then converted into ingredients and nutrient categories (*76–78*). To the best of our knowledge, there is a lack of comprehensive methods to both (i) understand the sustainability trade-offs of diets at the dish level and (ii) explore possible sustainable diet scenarios and their outcomes at the dish level.

Therefore, we developed an approach for estimating some of the key diet-related sustainability trade-offs at the dish level, using popular recipes in Japan. For each dish, we estimated the nutritional quality, price, and carbon footprint considering all the ingredients and cooking methods. We used different nutrient density scores (NDSs) to estimate nutritional quality, whereas the carbon footprint encompassed the direct and indirect carbon emissions of each dish. Subsequently, we explored how multiple dietary scenarios combining the study dishes could meet nutritional requirements while concurrently minimizing carbon footprint. Although the actual quantitative results of this analysis cannot be generalized easily outside of Japan, considering its unique culinary traditions, the underlying logic and methodological approach can be applied globally. We argue that such an approach could further complement general guidelines about appropriate food groups for a sustainable and healthy diet (e.g., the EAT-Lancet Commission Report) by providing more comprehensive information on sustainable diet composition in specific geographic contexts considering local realities.

RESULTS

Carbon footprints of major dishes

To estimate the carbon footprints of specific dishes, we combined information on emissions during the production of ingredients (indirect emissions) and those during cooking (direct emissions) (see Materials and Methods, step 1). The carbon footprints of the 45 popular dishes consumed in Japan considered in this study are divided into five major dish categories (Fig. 1). The estimated carbon footprints in Fig. 1 correspond to the amount of emissions for food served to one person (i.e., emissions per serving) and include emissions from cooking and emissions embodied in the ingredients.

The results indicated that beef-based dishes had the highest average carbon footprint, followed by chicken- and seafood-based dishes. Pork- and vegetable-based dishes had lower carbon footprints than those of other dishes. Although the relatively low carbon footprint of pork-based dishes can be counterintuitive due to the emission-intense characteristic of the pig husbandry, pork-based dishes in Japanese cuisine generally contain smaller meat portions, include many vegetables, and require a shorter cooking period. For example, in the pork-based dish "Mille Feuille hot pot (Nabe)," pork and Chinese cabbage accounted for 20.5 and 68.3% of the ingredients considering weight (excluding water), respectively. This is consistent with their proportions in other pork-based dishes, which explains, to a larger extent, their relatively lower, emissions than those of other meat-based dishes.

The results revealed that direct emissions from cooking had a much lower contribution to the overall carbon footprint of the dishes compared to indirect emissions (Fig. 1). Generally, direct emissions only account for 1.6 to 12.1% of the overall carbon footprint depending on the type of dish. Beef- and chicken-based dishes have on average, longer cooking times and higher direct emissions than those of other dishes. Overall, beef-based dishes had on average 18.5, 51.1, and 36.5% higher direct emissions than those of chicken-, pork-, and seafood-based dishes, respectively. Consistent with the results of indirect emissions, vegetable-based dishes had also on average the lowest direct emissions among dishes because considering that some vegetable dishes do not require cooking (e.g., "pickled Chinese cabbage" or "pickled nozawana").

Nutrition, carbon footprint, and price trade-offs at the dish level

Figure 2A presents the nutrient content of all dishes considered in the present study calculated on a per-serving basis. Furthermore, we standardized nutritional variables by factor considering the DRI values of the Japanese dietary guidelines. The forest plot in fig. S2 presents the nutritional value proportion of each dish (per one to three plates consumed) considering the recommended daily intake, thereby offering a comparative understanding of the nutritional contributions. This approach enabled us to reveal the disparities in nutritional provision across different dishes, offering a comprehensive comparison and ranking system for dishes based on their capacity to meet specific nutrient needs. The averages of nutrient contents of each dish group in the present study expressed as a proportion of the total daily recommended intake (%DRI) are presented in Fig. 2 (B and F). Generally, there were higher cholesterol levels in meat-based dishes than those in other dishes; however, there were considerable variations in certain nutrients within the same dish category (fig. S1). For example, cholesterol intake varied in each food category and was between 44.64 and 162.58%, 17.16 and 86.48%, 15.94 and 91.54%, 0.12 and 19.40%, and 11.80 and 232.8% of DRI for chicken-, beef-, seafood-, vegetarian-, and pork-based dishes, respectively. Similarly, the total salt content varied to a large extent and was between 6.75 and 67.86%, 3.23 and 219.29%, 13.33 and

76.52%, 3.41 and 86.63%, and 5.14 and 139.79% of DRI in chicken-, beef-, seafood-, vegetarian-, and pork-based dishes, respectively. Similar to the results observed for the carbon footprint, the wide variation in total salt content is attributed to the differences in the ingredients in each dish, which can affect the nutrient content of the dish, regardless of the major food type category in each dish (e.g., meat-, fish-, or vegetable-based).

Figure 3 presents the trade-offs for each dish on a per-serving basis. We used different NDSs to reflect the nutritional quality of each dish considering dietary preferences (see Materials and Methods, step 3) and its trade-off with the carbon footprint (total carbon footprint) and economic affordability (price).

Results in Fig. 3A reveal that there was no strong correlation between overall nutrient density (NDS-Tot; see Materials and Methods) and the carbon footprint. Beef- and chicken-based dishes were mostly distributed in quadrant I, indicating comparatively high nutritional scores and carbon footprints. Contrastingly, pork-, seafood-, and vegetable-based dishes had comparatively lower carbon footprints and NDS-Tot than those of other dishes, mostly distributed in quadrant III. However, some of the most noteworthy patterns were the five dishes distributed in quadrants IV, which included two pork-based dishes ("Mille Feuille hot pot (Nabe) with pork" and "Chinese cabbage and Chinese restaurant stir-fried meat and vegetables"), one beef-based dish ("meat and potatoes"), one seafood-based dish ("boiled mackerel miso"), and one vegetable-based dish ("bamboo shoots, butterbur, and wakame seaweed"). These dishes had comparatively higher nutrient contents than those from other quadrants while generating relatively lower carbon footprints. Of these, vegetarian ("bamboo

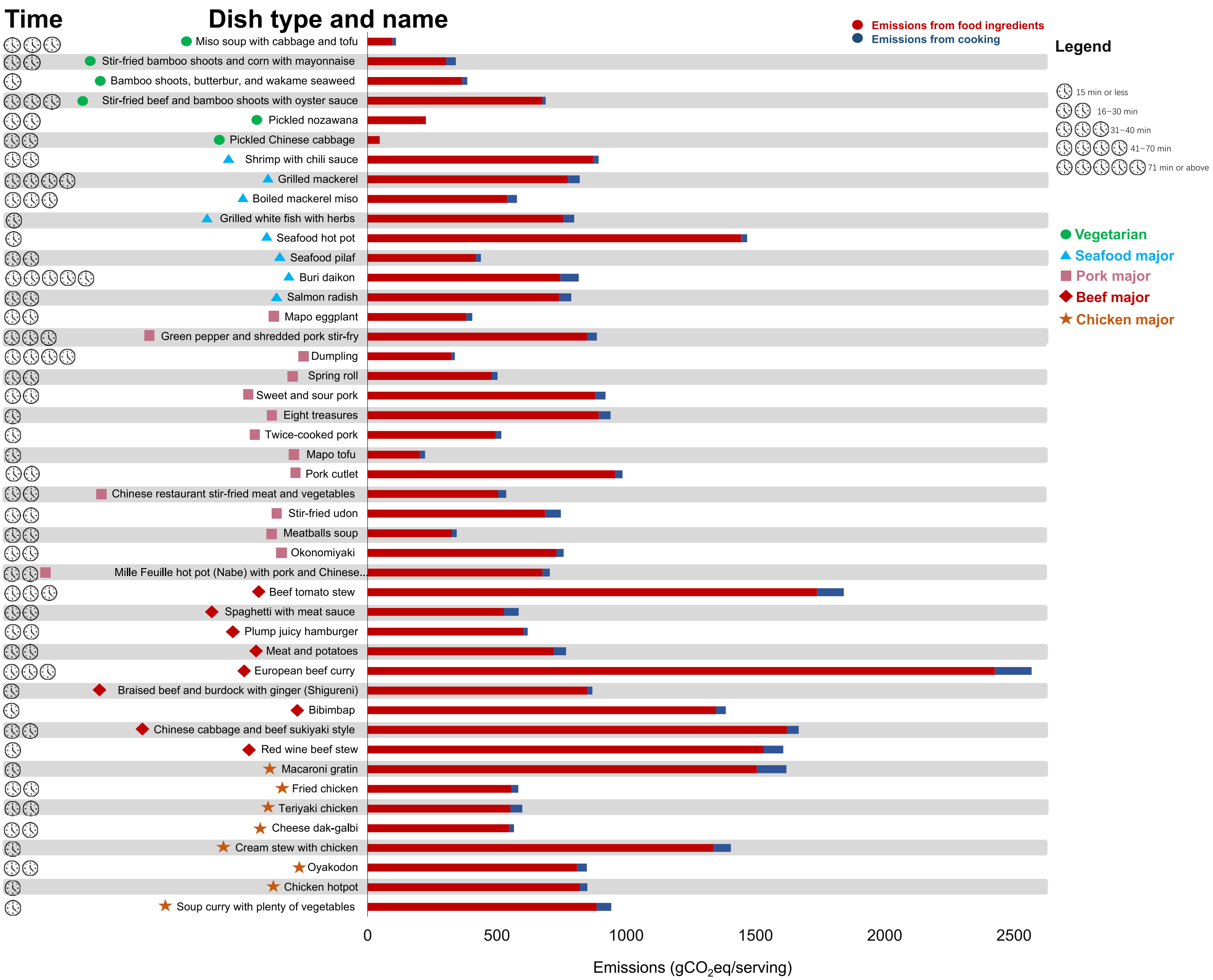

Fig. 1. Carbon footprints of major dishes consumed in Japan. The clocks in the left column indicate the cooking times for each dish in increments of 15 min. The stacked horizontal bars represent the carbon footprints of each dish per serving (in gCO_2-eq per serving). The blue portions of the stacked horizontal bars indicate the direct emissions associated with cooking, and the red portions indicate the indirect emissions from food ingredient production. The five categories of dishes are indicated by different colors and shapes. For recipes with more than one serving, we proportionally divide the total direct and indirect emissions by the number of servings. Table S1 contains the original recipe information, including the total amount of ingredients and the total number of servings.

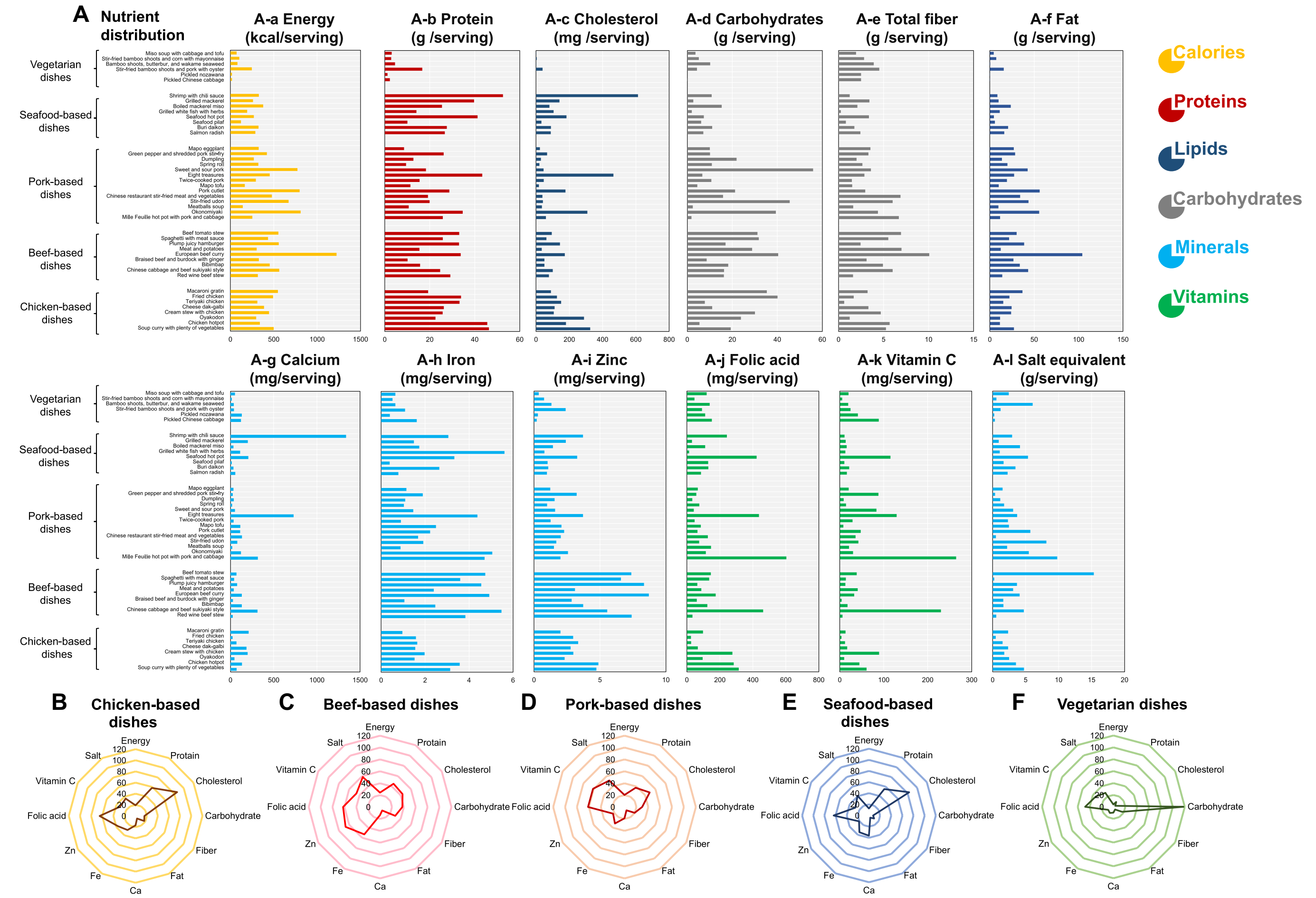

Fig. 2. Nutrient content of studied dishes and average nutritional distribution by dish category. (**A**) Nutrient content per serving for the studied dishes. The 12 nutrients are classified into six main groups, namely, calories per serving (in yellow), protein per serving (in red), lipids per serving (in dark blue), carbohydrates per serving (in gray), minerals per serving (in light blue), and vitamins per serving (in green). (**B** to **F**) Wind rose diagrams of the average per serving nutrient content of the five major dish categories as a percentage of the Dietary Reference Intake (DRI) recommended by the Japanese Ministry of Health, Labor and Welfare (see table S2). The DRI values are adjusted considering age groups, gender, and other nutritionally important demographic categories (e.g., pregnant women) using the current demographic structure of the Japanese society (see Materials and Methods, step 2).

shoots, butterbur, and wakame seaweed") and beef dishes ("meat and potatoes") are cheaper and have many benefits. Contrastingly, there were seven dishes in quadrant II (two chicken-, two beef-, two pork-based dishes, and one seafood-based dish) with limited nutrients and impact on the environment.

The patterns of the NDS-Tot of most dishes considering their prices were consistent with the carbon footprint patterns outlined above, indicating that dishes with higher carbon footprints are generally more expensive. For instance, beef-based dishes generally had high NDS-Tot scores and prices and were mostly distributed in quadrant I (Fig. 3A), whereas vegetable-based dishes generally had lower NDS-Tot scores and prices than those of other dishes and were mostly distributed in quadrant III (Fig. 3A). While seafood-based dishes were associated with NDS-Tot scores close to the weighted averages of all dishes (mainly distributed in quadrant III; Fig. 3A), they are relatively affordable. However, some exceptions for dishes (e.g., "boiled mackerel miso and shrimp with chili sauce") are distributed in quadrant IV (Fig. 3A), indicating that some dishes are affordable sources of protein. Although beef- and chicken-based dishes had higher NDS-Tot, they were expensive, with a high carbon footprint and higher environmental costs than those of other dishes.

Panels B to D in Fig. 3 present the trade-offs among nutrient quality, carbon footprint, and prices for different NDS (see Materials and Methods, step 3). Low-calorie diets had trade-offs among the carbon footprint, prices, and nutrient quality (Fig. 3B). Few vegetable-based dishes had high NDS-Eng and low carbon footprints (quadrant IV) and low prices, making them preferred among other diets. Some pork-, chicken-, and seafood-based dishes had reasonably high NDS-Eng values with relatively low carbon footprints (mainly distributed at the boundaries of the quadrants). Contrastingly, beef- and several chicken-based dishes have low NDS-Eng values, high carbon footprints, and relatively high prices (distributed in quadrant II), making them unsuitable for low-calorie diets.

Figure 3C reveals that vegetarian dishes scored much higher NDS-Cho scores than many other dishes, owing to the extremely low cholesterol content in their ingredients (e.g., the highest-scoring dish comprising of bamboo shoots, butterbur, and wakame seaweed weighed approximately 1000 g and had 0.29 mg of cholesterol),

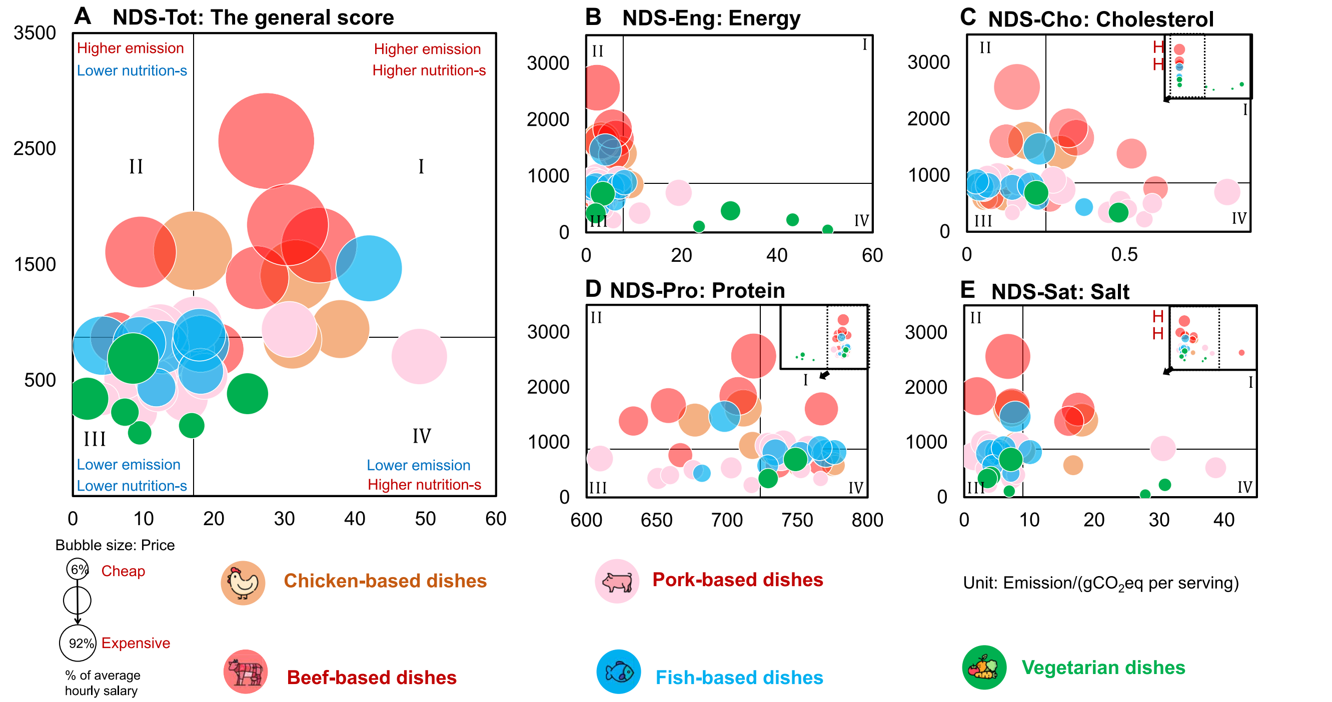

Fig. 3. Trade-offs between nutrition, price, and carbon footprints for studied dishes. *x* axes denote different NDS scores per serving and the *y* axes denote emissions per serving (in gCO_2-eq per serving). Each bubble indicates a specific dish. The color of each bubble indicates the category of the dish (e.g., red for beef-based dishes), and the size of the bubble indicates the price of a serving of each dish considering the average hourly salary rate in Japan (see bottom of the figure). (**A**) The relationship between the carbon footprint and the overall nutrient density (NDS-Tot) of the dishes. The four quadrants in this panel denote: high total nutrient density and high carbon footprint (quadrant I), low total nutrient density and high carbon footprint (quadrant II), low total nutrient density and low carbon footprint (quadrant III), and high total nutrient density and low carbon footprint (quadrant IV). (**B** to **E**) The relationships between the carbon footprints and the nutritional density scores of the dishes for specific foci, namely, energy [NDS-Eng, (B)], cholesterol [NDS-Cho, (C)], protein [NDS-Pro, (D)], and salt equivalent [NDS-Sat, (E)]. The four quadrants in each of these panels denote: (i) high specific nutrient density and high carbon footprint (quadrant I), (ii) low specific nutrient density and high carbon footprint (quadrant II), (iii) low specific nutrient density and low carbon footprint (quadrant III), and (iv) high specific nutrient density and low carbon footprint (quadrant IV). The quadrants in all panels are divided based on the mean values of carbon footprints and nutrient densities rather than value judgments of what constitutes high or low nutritional quality or carbon footprints. Table S3 outlines the dishes in each quadrant of each panel.

limiting dietary cholesterol. Some of these very low cholesterol outliers were removed from Fig. 3C (see the left side of a small insert for their relative position) to visualize better the NDS-Cho scores (low cholesterol intake) for other dishes. We see again that for the reasons outlined above (e.g., comparatively small meat content) some pork-based dishes had relatively low cholesterol levels compared with those of chicken- and seafood-based dishes (e.g., "Mille Feuille hot pot with pork and Chinese cabbage" had NDS-Cho score of 0.82). For instance, seafood-based dishes were mainly distributed in quadrants III and II, except for "seafood pilaf," which was distributed in quadrant IV with low cholesterol, carbon footprint, and price.

The NDS-Pro results (high-protein intake) of different dishes are presented in Fig. 3D. The thumbnails in the upper-right corner of Fig. 3D revealed that the NDS-Pro scores of vegetable-based dishes were much lower than those of other dishes. Furthermore, most seafood-based dishes were located in quadrant IV, except for a few with extremely low NDS-Pro values, revealing the characteristics of protein-rich, low-carbon footprint, and cheap dishes in this category. Although beef and chicken are inherently protein-rich (*79*, *80*), the results revealed that beef-based dishes are not good protein sources, as they were mostly distributed in quadrant II and were relatively expensive. The NDS-Pro scores of pork dishes fluctuated substantially due to the reasons mentioned above (e.g., low meat content for some dishes).

Figure 3E shows that the highest NDS-Sat was for a beef-based dish (right side of small insert) followed by two pork-based and two vegetarian dishes, all distributed in quadrant IV, indicating their superiority considering carbon footprint and price. Contrastingly, dishes in quadrants II and III had high salt equivalents scores. Specific information on the characteristics of the dishes in quadrants II and III, mainly consisting of beef-, pork-, and seafood-based dishes, is presented in table S4. Although most pork-based, seafood-based, and vegetarian dishes had lower salt equivalent scores, their carbon footprints were lower than those of beef-based dishes.

Mixed diet scenarios meet nutritional requirements and minimize carbon footprints

The final step of our analysis was to provide insight into how healthy and sustainable diets might appear in Japan at the dish level (see Materials and Methods, step 4). We explored 16 dietary scenarios consisting of different combinations of dishes (i.e., three meals/cap per day) that meet nutritional requirements while minimizing the carbon footprint (see Materials and Methods, step 4). For each diet scenario, we identified all possible combinations of relevant dishes. The five combinations with the lowest emissions are discussed in the present study to avoid bias caused by a single combination result. Therefore, combinations with the lowest emissions are presented in table S5. The nutrient contents and carbon footprints of diets are presented in tables S6 and S7.

Figure 4 presents the average performance of the five combinations of dishes with the lowest emissions for each diet scenario while simultaneously meeting all DRIs or constraints (represented by the purple-colored ranges in each panel). All 16 diet scenarios contained combinations of dishes that simultaneously met all dietary requirements or constraints, with some notable exceptions. For example, the chicken-based diet did not meet the cholesterol intake requirement (Fig. 4D), the seafood-based diet did not meet the cholesterol and salt intake requirements (Fig. 4, D and L), or the vegetarian-based diet did not meet the folic acid and salt intake requirements (Fig. 4, J and L). Furthermore, many diets contain dish combinations with average performances exceeding the daily recommended value for nutrients such as proteins, irons, or vitamin C. Conversely, we observed some notable exceptions in diets with dish combinations that increase the intake of important constraints, such as cholesterol or salt-equivalent intake. While some seem expected, such as beef-chicken diet dish combinations exceeding the recommended cholesterol intake (Fig. 4D), others appear counterintuitive at first, for example, seafood diet exceeding cholesterol (Fig. 4D) and salt-equivalent (Fig. 4L) recommended intakes or vegetable diet exceeding the salt-equivalent recommended intake (Fig. 4D). These findings could be because vegetables and fish contain low cholesterol or salt levels while at the ingredient level; however, the actual dishes contain several other ingredients such as soy sauce in "seafood hot pot," raw seaweed, and Japanese soup stock in "bamboo shoots,

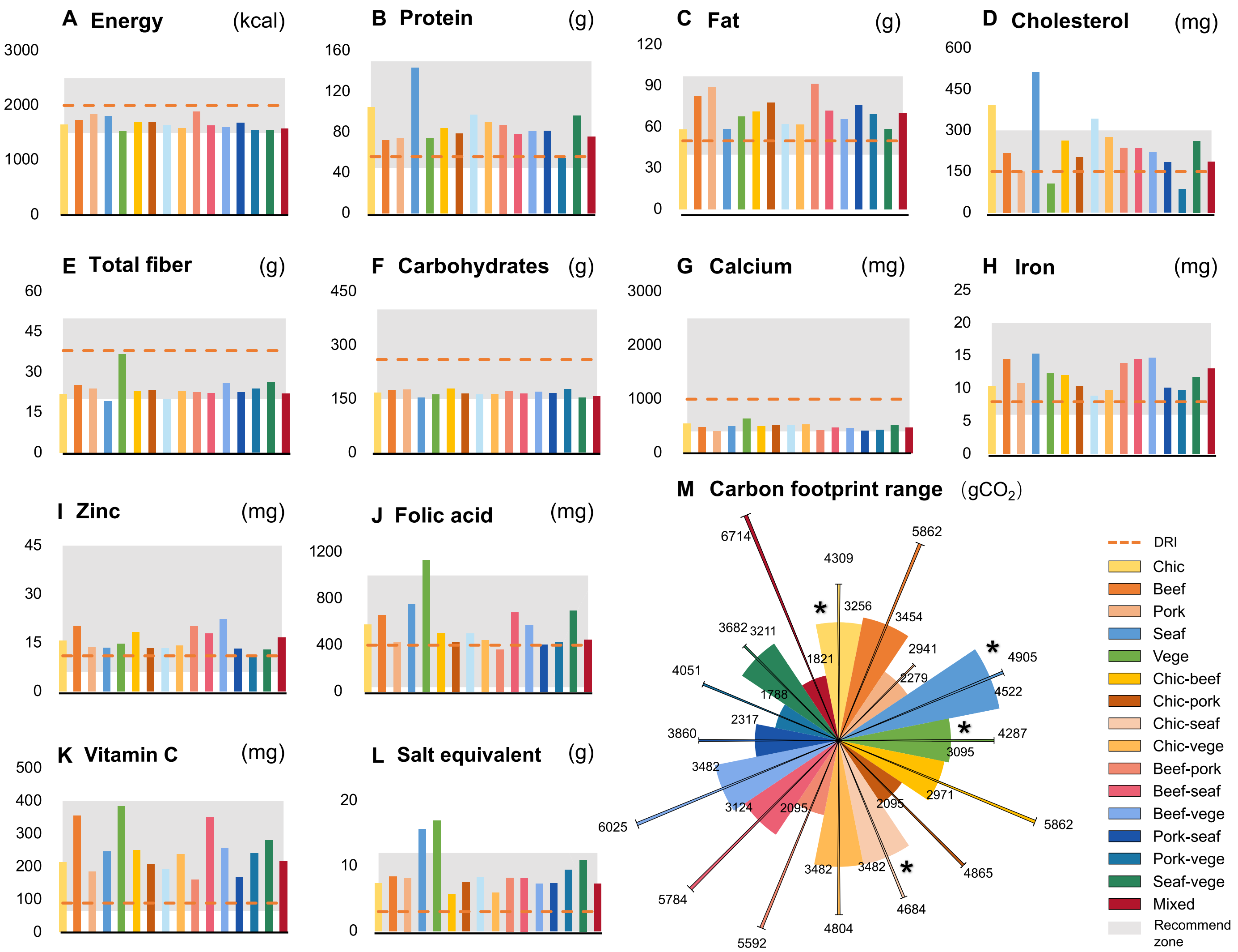

Fig. 4. Nutritional and environmental performance of dish-based diet scenarios. (**A** to **L**) Nutrient content of the 16 dish-based scenarios compared to the daily recommended intake (DRI), and (**M**) the carbon footprint range of dish combinations meeting the nutritional requirements for each of the 16 dish-based diet scenarios. Each diet scenario reflects relevant combinations of the 45 studied dishes (e.g., the "beef" scenario contains combinations of the nine beef-based dishes, and the "beef-chicken" scenario contains combinations of the nine beef- and the eight chicken-based dishes). The gray zone in (A) to (L) represents the recommended range for daily recommended intake (DRI), whereas the dotted orange lines indicate the DRI for each nutrient. In (M), "*" indicates diet scenarios where no dish combination can meet simultaneously all nutrient requirements and hence entail loosened nutrition content constraints. In each panel, the bars/pedals indicate the average nutrition performance of the five combinations with the lowest carbon footprint, which meet nutritional requirements for all nutrients or constraints simultaneously (see table S5 for relevant combinations for each scenario).

butterbur, and wakame seaweed" that increases cholesterol and salt levels (table S1).

Figure 5 presents the carbon footprint distribution of all dish combinations meeting the nutritional requirements for each diet scenario, while the range is presented as a pie chart in Fig. 4M. In the present study, several diets that met nutrient requirements contained dish combinations that were at the lower end of the carbon footprint distributions, for some diets the carbon footprint distributions were skewed toward the higher end of the spectrum. For example, diets with generally lower carbon footprints included vegetarian (Fig. 5E), pork-seafood (Fig. 5M), and pork-vegetable (Fig. 5N). Conversely, diets with generally higher carbon footprints included almost all diets with beef dishes (Fig. 5, F and J to L). Here, we need to point to some counterintuitive results, such as the generally higher carbon footprints of diets with seafood dishes (Fig. 5D) or the lower carbon footprints of some diets containing pork dishes (Fig. 5, G, M, and N). The reason is that although the base ingredients, such as pork or seafood, have generally high or low emissions respectively, their dishes contain other many ingredients or require specific cooking processes that affect the actual carbon footprints at the dish level (Fig. 1). Overall, mixed diets contained more dish combinations at the lower end of the carbon footprint spectrum (Fig. 5P) compared to more restrictive diets. Furthermore, mixed diets, had more combinations of dishes that met nutritional requirements ($n = 771$) more restrictive diets.

DISCUSSION

The present study proposes a methodological approach to identify trade-offs in dietary choices based on optimization modeling. It explores the nutritional and environmental outcomes of different dietary scenarios at the dish level rather than common approaches that rely on food groups (e.g., plant-, fish-, and meat-based diets). By combining diverse datasets, we explored the trade-offs among the nutritional quality, carbon footprint, and price of 45 commonly consumed dishes in Japan and the possible outcomes of 16 dietary scenarios combining these dishes. We argue that although broad-based diet scenarios that focus on food groups can reveal what a sustainable diet might look like and the general direction to achieve them, dietary recommendations that aim at enabling dietary shifts would benefit from more fine-grained approaches that provide information for healthy and sustainable recipes considering cultural preferences and the local availability of food items in different national contexts. As

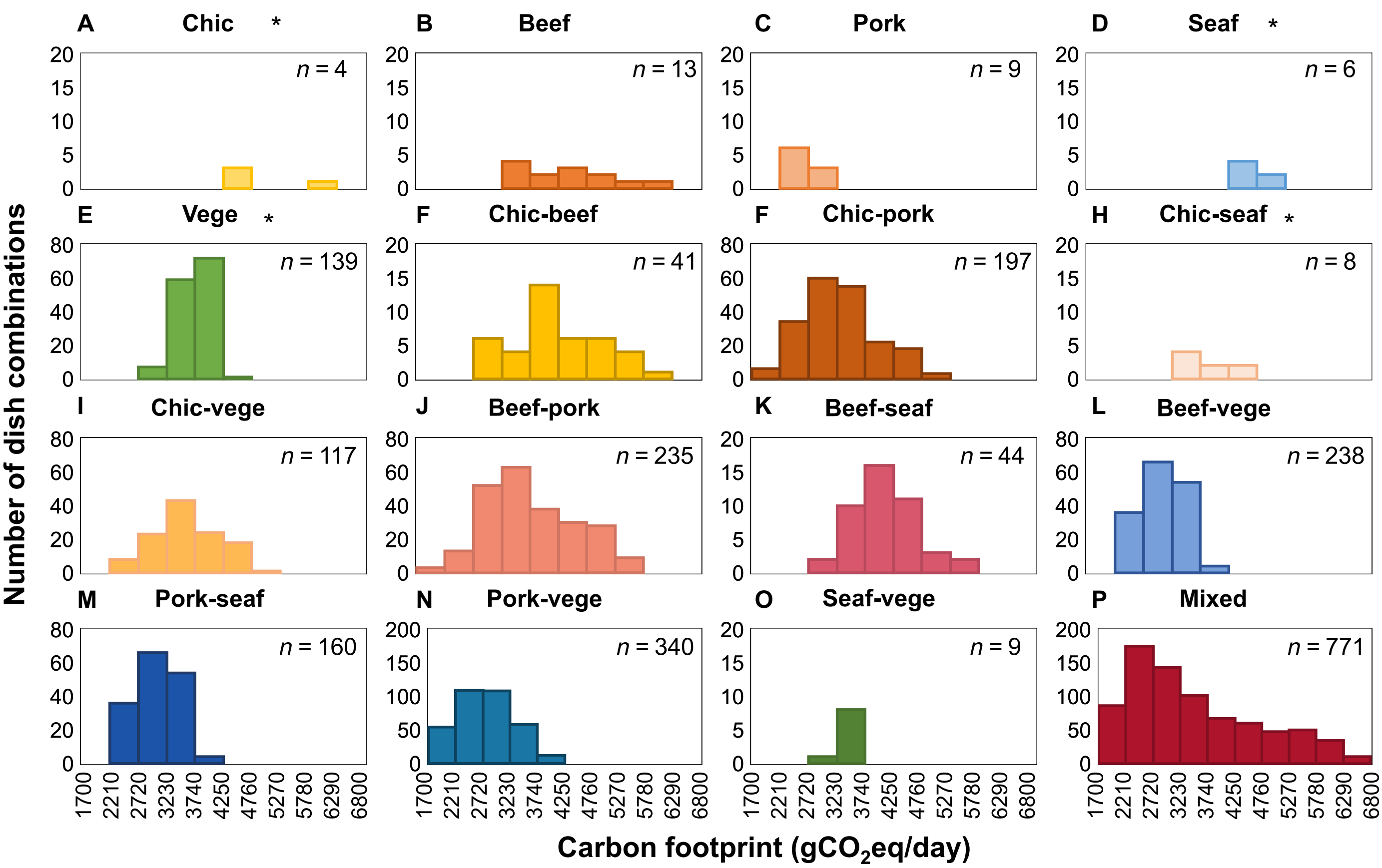

Fig. 5. Carbon footprint of dish-based diet scenarios. (**A** to **P**) Each scenario reflects diets based on relevant combinations of the 45 studied dishes. The *x* axis indicates the carbon footprint of dish combinations (gCO_2eq/day) that meet simultaneously all nutrient requirements; the *y* axis denotes the number of dish combinations in different carbon footprint ranges; *n* refers to the total number of dish combinations in each dish-based diet scenario that meet simultaneously all nutrient requirements (e.g., for the "beef" scenario, there are 13 dish combinations that meet nutrient requirements; for the "beef-chicken" scenario, there are 41 dish combinations that meet nutrient requirements). "*" indicates diet scenarios for which no dish combination meets simultaneously all nutrient requirements. Sample dish combinations for each scenario that meet nutritional requirements are included in table S7.

discussed below, our dish-based approach can complement existing broad diet-based approaches and facilitate the identification of pathways to achieve sustainable diet change.

At the dish level, our results have exhibited convergences and divergences with existing literature. For example, the results of the estimated environmental impacts were not always consistent with those of previous studies. On the one hand, we estimate high carbon footprints for beef-based dishes (Fig. 1) and diets (Fig. 5, B, J, and K) that agree with the general consensus in the literature that diets rich in beef have some of the highest emissions and environmental impact (*81*–*83*). Similarly, we estimate some of the lowest carbon footprints for plant-based dishes (Fig. 1) and diets (Fig. 5, E and I). However, unexpectedly, we estimate low carbon footprints for some pork-based dishes (Fig. 1) and diets (Fig. 5, E, M, and N), which seems to contradict previous studies correlating pork consumption with high emissions (*19*, *84*). This can be explained by considering the full set of ingredients in each dish. For example, in Japan, pork-based dishes contain many ingredients, including large amounts of vegetables and relatively modest portions of meat, which lower the overall carbon footprint at the dish level. We also notably find for all types of dishes that indirect emissions constitute the bulk of the carbon footprint, while direct emissions from cooking contribute, on average, only between 1.6 and 12.1% of the total carbon footprint (Fig. 1). For example, although beef- and chicken-based dishes had on average the highest direct emissions from cooking, their direct emissions were much lower than the indirect ones.

Our results move beyond broad-based recommendations for sustainable diets, such as increasing the consumption of plant-based food (*19*, *85*–*87*) and seafood (*24*, *27*, *86*), and decreasing meat consumption (*17*, *19*, *85*, *87*). They do so by revealing how such recommendations can perform in terms of nutrition and carbon footprints (Figs. 4 and 5). The results revealed that mixed diets contained a larger combination of dishes meeting the nutrient requirements than more restrictive diets (Fig. 4). Furthermore, mixed diets had a comparatively high combination of dishes distributed at the lower end of the carbon footprint spectrum (Fig. 5P). This reflects to some extent the conclusion of the EAT-Lancet Commission report that a balanced diet containing plant-based food with fewer animal-based ingredients can improve health and environmental outcomes (*17*, *81*). Moreover, diversified diets may lead to a more comprehensive distribution of amino acids, due to their wider variety of ingredients from plant and animal sources (*82*, *83*). Essentially mixed diets seem to give consumers greater flexibility in preparing healthy and environmentally sustainable diets than more restrictive ones.

In theory, the nuanced information about the carbon footprint of dishes presented in this study can be very useful to consumers who want to switch to healthier and more sustainable diets, as well as stakeholders who want to catalyze such dietary transitions. The accuracy of these estimates can be further improved by (i) calculating variations of the same dish or recipe to account for personalized tastes, (ii) estimating the relative impacts of different cooking methods and ingredients based on prevailing market options (*88*), and (iii) integrating information about the relative dish preferences of different demographic and socioeconomic segments. The latter can be particularly important in countries that undergo rapid demographic shifts such as Japan. As a case in point, studies have shown that the elderly in Japan tend to have specific consumption habits for certain food groups, which affect substantially the emission profiles of their diets (*89*, *90*).

In practice, however, we lack important insights about the actual acceptability and usability of this type of information among consumers. Most studies that have explored the carbon footprints of dishes have mostly focused on the actual quantification process (*73*–*75*). We still lack a good understanding about what tools and information everyday consumers might need to use effectively information about the carbon footprint of dishes, and other related trade-offs. For example, studies in similar contexts (e.g., carbon labeling of meals) have noted that although this information might influence more climate-friendly meal/dish choices, sometimes the effects are not obvious and/or there is large variability in how consumers perceive, accept, and use such information, and thus the extent to which this information can contribute to the decarbonization of diets (*91*).

Here, we need to point out that although our dish-based approach deviates from more conventional approaches relying on broad food groups, it must not be viewed as antagonistic or mutually exclusive. Instead, we believe that the two approaches are highly complementary. In our opinion, approaches relying on food groups can broadly indicate what constitutes sustainable diets and how to achieve them at the production level; thus, pointing to feasible directions for transforming food systems at the global and international levels, considering planetary boundaries (*7*). At the same time, we believe that dish-based approaches can help improve the operationalization of diet scenarios that use food groups at the national and sub-national levels, by acting as reality checks and avenues to inform, design, and convey feasible and acceptable sustainable dietary change pathways. As discussed above, our results identified both divergences and convergences in the carbon footprint of some dish categories and diet scenarios, when compared to their broad food groups. Dish-based approaches can better reflect: (i) how food is actually prepared and consumed in a given national context considering cultural preferences [e.g., culinary preferences for certain tastes or cooking methods, cultural (un)acceptability of certain food items] and (ii) what is the availability of certain food items (e.g., availability of specific vegetables considering climate). The complementarity of the two approaches can be further explored through comparative studies that use both of them to estimate the impact of historical and future diet changes and downscale the recommendations of broad-based scenarios and sustainable diets (e.g., EAT-Lancet diet) to create dietary options that suit individual national contexts.

Last, we need to acknowledge that the present study focused only on the Japanese context. Japanese cuisine has been shaped by a long history of culinary traditions and cultural practices and is thus quite unique. As dietary habits, recipes, nutritional requirements, and availability of food ingredients can differ greatly across countries, the direct transfer of the actual quantitative results may not be universally applicable beyond Japan. However, the methodological framework presented here has broad applicability and potential global relevance. Such a detailed dish-based approach that relies on national data can be adapted to any country or region, assuming that the requisite data are available. Future studies should tailor and apply this (or similar) framework to other culinary traditions and dietary practices to enrich the global understanding of the environmental impacts of dietary choices and the potential mitigation strategies across cultural and national contexts.

MATERIALS AND METHODS

Research approach

The present study aimed to identify the trade-offs inherent in dietary choices in Japan considering emissions, nutrition, and price at the dish level, as this is the level at which individuals make dietary choices and consume food. Arguably this type of trade-off analysis can offer more nuanced information for dietary recommendations that simultaneously consider human health, environment, and economy.

To investigate the trade-offs in dietary choices, we used 45 dishes: chicken-based (n = 8), beef-based (n = 9), pork-based (n = 14), seafood-based (n = 8), and vegetable-based (n = 6). These dishes represent the most popular dishes selected by the Ajinomoto Company in Japan, one of the largest food companies globally (https://park.ajinomoto.co.jp/). The selected dishes are listed in table S6. We divide the 45 dishes across the five dish categories based on the main ingredient of the recipes. For instance, although a dish that contains beef may also contain a substantial amount of vegetables, the vegetables are generally considered a complementary component to the beef, and the dish is categorized as a beef-based dish. The analytical procedure used in the present study followed four major steps, which are summarized below and comprehensively explained in the following sections.

First, we estimated the carbon footprint of each dish as the sum of the direct emissions from cooking and the indirect emissions embodied in the ingredients and items used in each dish (step 1). We estimated the indirect emissions associated with locally produced items and those imported into Japan, considering upstream production.

Second, we estimated the nutrient content and price of each dish by summing the nutrient contents and prices of all ingredients used in the dish (step 2). Nutrient contents were calculated using the information provided by the Dietary Reference Intakes (DRIs) for Japanese population (Ministry of Health, Labor, and Welfare, Japan).

Third, we estimated the nutritional quality of each dish using different nutrient densitys (NDS) (step 3). Beyond the standard NDS (NDS-Tot in the present study), we developed four variations to reflect the specific demands for low-calorie diets (NDS-Eng), low-cholesterol diets (NBS-Cho), high-protein diets (NDS-Pro), and low-salt diets (NDS-Sat).

Following the estimation of the carbon footprint, price, and nutritional quality of each dish during steps 1 to 3, we visualized these dimensions in bubble diagrams to help identify the expected trade-offs among these dimensions (Fig. 3).

Fourth, we explored the performance of 16 sample dietary scenarios consisting of different combinations of the 45 dishes (step 4). To achieve this we established a mathematical optimization model that compares the nutritional and carbon footprints of the 16 diet scenarios.

Carbon footprints of selected dishes (step 1)

The overall per-serving carbon footprint of each dish consumed in Japan was calculated as the sum of the indirect (E_{cf}) and direct (E_{d}) emissions (Eq. 1)

$$E = \frac{(E_{\mathrm{d}} + E_{\mathrm{cf}})}{C} \tag{1}$$

where C denotes the number of servings specified in the dish, which is essentially a per-serving estimate of the carbon footprint of consuming a specific dish. In simple words, we sum up the direct and indirect emissions for each dish and divide them by the number of servings in each dish to calculate the per-serving carbon footprint.

The indirect emissions (E_{cf}) of a specific dish is the sum of all the indirect emissions correlated with the individual ingredients of the dish (see the "Research approach" section and below), including condiments and spices

$$E_{\mathrm{cf}} = \sum_{i=1} Q_i \times E_i \tag{2}$$

where i denotes the individual ingredients used in the dish, Q_i indicates the quantity of item i used in the dish, E_i represents the indirect emissions of CO_2 by item i per gram. We accounted for emissions associated with the domestic production of individual food items and those imported (see the previous section)

$$E_i = p_i \times [(E_{di} \times (1 - I_i) + E_{oi} \times I_i] \tag{3}$$

where p_i is the unit market price of item i [collected from the Ministry of Agriculture, Forestry, and Fisheries, Japan (*92*)], and E_{di} and E_{oi} denote the emission intensity of food items from domestic and imported sources, respectively. I_i indicates the import index of food items derived from the 2015 input-output table of the Japanese Ministry of Internal Affairs and Communication, Japan (*93*).

We used 2015 data from the Japan-specific (3EID) and global (EXIOBASE) input-output tables to comprehensively estimate the indirect emissions of food ingredients used in Japan. This is to reflect the fact that many food value chains span national boundaries, in that food items produced in country A can be exported and consumed in country B. The 3EID table allows for a comprehensive and very detailed estimation of the indirect emissions of food ingredients or commodities produced only in Japan. Conversely, the EXIOBASE database can be used to estimate the emissions of those food items imported into Japan. Combining these datasets is necessary for the accurate estimation of indirect emissions of food ingredients and commodities in Japan, considering that it largely depends on imports for many food items, particularly some widely consumed emission-intensive commodities, such as beef or other meat from other ruminants (FAOSTAT, 2022).

In more detail, the emission intensity database of 3EID is developed by the National Institute of Environmental Studies, Tokyo, Japan, and contains information on >500 food items, which perfectly covers the ingredients of almost every dish consumed in Japan. EXIOBASE was developed by the EXIOBASE consortium (*94*), a multiregional input-output table that can source transboundary emissions. The emission intensity database calculated using EXIOBASE contains information on approximately 37 food items, including the main food commodities imported into Japan.

In terms of emissions estimation, the Japanese component of indirect emissions was first captured through the 3EID input-output table using Eq. 4

$$\begin{pmatrix} f_1^{\mathrm{indirect}} \\ \vdots \\ f_n^{\mathrm{indirect}} \end{pmatrix}^{\mathrm{transpose}} = \mathbf{D}\left[\mathbf{I} - (\mathbf{I} - \overline{\mathbf{M}})\mathbf{A}\right]^{-1} \tag{4}$$

where $f_{n,t}^{\text{indirect}}$ indicates the indirect carbon footprint intensity of food item n; $\mathbf{D}$ denotes the diagonal matrix of direct emission. $\mathbf{A} = [A_{ij}] = \left[\frac{x_{ij}}{X_j}\right]$, where x_{ij} is industry i's output needed to produce per unit of industry j's output, X_j is the total output of sector j, and $\overline{\mathbf{M}}$ is the diagonal matrix denoting the direct requirement coefficients for imported goods.

We adopted the purchaser-based price for food items to calculate emissions from household consumption. The expenditure for each food item was collected from the Family Income and Expenditure Survey [FIES; (*95*)] dataset, a monthly representative household survey conducted by the Statistics Bureau of Japan to capture household income and expenditure. Next, monetary consumption was multiplied by the indirect emissions embodied in the household's consumption of goods and services via the 3EID dataset (*96*) (for domestic production) and the EXIOBASE dataset (for imports). The classification of major food categories in the EXIOBASE and sector aggregation from the EXIOBASE are listed in tables S8 and S9. There were differences in the number and classifications of food items covered in the 3EID, EXIOBASE, and FIES. Therefore, it is necessary to cross-map across similar food items to calculate the indirect emissions. The cross-mapping of items in the FIES and 3EID datasets is presented in table S10.

As described previously, $\overline{\mathbf{M}}$ is included in Eq. 1; therefore, the carbon footprints of imported food items should be accurately reflected. Therefore, we estimated the indirect emission components associated with imported food items through EXIOBASE using Eq. 5

$$\begin{pmatrix} E_{1,C1}^{\text{indirect}} \\ \vdots \\ E_{j,Cn}^{\text{indirect}} \end{pmatrix} = \mathbf{D}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{F}_{\text{Japan}}^{\text{food}} \tag{5}$$

where the $\mathbf{F}_{\text{Japan}}^{\text{food}}$ indicates the $n \times 1$ vector of the Japanese final consumption of food items, $(\mathbf{I}-\mathbf{A})^{-1}$ refers to the Leontief inverse matrix. The generated vector $\mathbf{E}_{j,Cn}^{\text{indirect}}$ refers to the indirect emissions of food items from country n (Cn)'s sector j. Because Eq. 1 provides the domestic emissions intensity and the $\mathbf{E}^{\text{indirect}}$ vector excludes Japan's domestic emissions. The indirect emissions for food items imported into Japan can be expressed as $k_n^{\text{indirect}} = \sum \sum \frac{E_{j,Cn}^{\text{indirect}}}{X^{\text{Japan}}}$, where X^{Japan} is the total output of Japan. Therefore, for one unit of food item consumed in Japan, the indirect emissions were calculated using Eq. 6 as follows

$$T_n^{\text{indirect}} = M_n \times R_{\%}^d \times f_n^{\text{indirect}} + M_n \times R_{\%}^o \times f_n^{\text{indirect}} \times k_n^{\text{indirect}} \tag{6}$$

where T_n^{indirect} is the total indirect emissions for food item n; M_n refers to the monetary consumption of food item n; $R_{\%}^d$ is the ratio of domestic production for food item n; and $R_{\%}^o$ is the import ratio for food item n, with $R_{\%}^d + R_{\%}^o = 1$.

The EXIOBASE provides information on a wide range of atmospheric emissions, including GHG emissions (e.g., CO_2, CH_4, N_2O, SOx, NOx, and NH_3), particulate matter (e.g., PM_{10} and $PM_{2.5}$), and heavy metals (e.g., Pb, Cr, and Cu). For carbon footprint analysis, emissions were expressed considering CO_2 equivalents (CO_2eq), covering the emissions of CO_2, CH_4, N_2O, SOx, NOx, NH_3, HFCs, PFCs, SF_6, and NF_3.

Direct emissions occur through the direct and indirect use of fossil fuels such as natural gas or electricity for cooking. In the present study, we used liquefied petroleum gas (LPG) stoves as the basis for estimating direct emissions from cooking different dishes as follows

$$E_d = 0.058 \times E_{\text{lpg}} \times G \times T \tag{7}$$

where 0.058 is the mass-energy conversion rate of LPG (from kilograms to gigajoules), E_{lpg} is the emission intensity of LPG, G is the gas use per hour derived from an example gas oven (https://eurafrican.co.za/product/gas-oven-60cm-gfeg31ix/) and T is the time used for cooking according to the reference dishes (table S1). The direct emissions were calculated considering the information provided in the dishes regarding cooking times and associated energy consumption (gas and electricity) rather than the actual energy use. The cooking time and emissions considered in our calculations included the actual heating time and did not include possible ingredient preparation (e.g., cutting or washing of ingredients) or related emissions. Common energy carriers used for cooking are LPG, natural gas, and electricity. Acknowledging that different carriers may generate different emissions, we used LPG for this analysis, as it is the major cooking fuel used in Japan. There was no record in the FIES of the type of energy used during cooking. However, we expect the energy carrier to have a small effect on the overall carbon footprint results, as the direct emissions associated with the cooking process only account for 0 to 12.1% of the overall carbon footprint of each dish.

Nutrient content and price estimation (step 2)

We evaluated the price and nutrient content per serving for each dish, equivalent to the per-serving nutrient intake and cost. We added the prices of the different ingredients (including minor ones such as spices and condiments) and cooking fuel cost, as specified in the base dish, and divided it by the number of servings to calculate a per-serving estimate. The unit price data for each ingredient were derived from the average price of the FIES, which is the same source used for the household consumption inventory (see step 1). We expressed the cost of a serving, considering the mean hourly wage in Japan.

Nutrient intake was estimated at the per-serving level (equivalent to per capita) by adding the nutrient contents of all ingredients, including the nutrients in all ingredients specified in the dish, including minor ones such as spices and condiments as follows

$$N_J = \frac{\sum_{i=1,j=1} Q_i \times N_{ij}}{C} \tag{8}$$

where J denotes the nutrient category, and j is the specific nutrient item under category J. In the present study, we mainly investigated 10 variables: energy content, protein content, the amino acid composition of proteins, dietary lipids, cholesterol, lipids, carbohydrates, total fiber, vitamin C, and salt equivalents. N_{ij} is the unit value of a specific variable for food item i derived from the Food Composition Database supported by the Japanese Ministry of Education, Culture, Sports, Science, and Technology (*96*). For nutrients that could not be measured or were in trace quantities, we assigned zero to the unit value of specific nutrients (*97*).

Nutritional quality assessment (step 3)

We used the NDS to evaluate the aggregate nutritional quality of the different dishes (*98*, *99*). The NDS assesses the contribution of each dish to the intake of multiple nutrients required by the human body by comparing the nutrient content of each dish with the DRI values. Generally, the NDS is calculated considering the nutrient content per unit weight or energy of food (*75, 99*, *100*). Drawing on the concept of NDS, we developed four NDS sub-scores that reflect common dietary requirements or controls: energy, cholesterol, protein, and salt (see below for justification). Five NDSs were developed to calculate the nutrient quality of the selected dishes.

First, the NDS-Tot was calculated considering the correlation between the total nutrient content of the dish and the recommended nutrient intakes required by the human body. Nutrients are classified into two groups: desirable and undesirable nutrients (see below for distinction)

$$\text{NDS}-\text{Tot}=\sum_{i=1}^{x}\frac{\text{Nutrient } i}{\text{DRI } i}-\sum_{j=1}^{y}\frac{\text{Nutrient } j}{\text{MRI } j} \tag{9}$$

where x represents desirable nutrients, y represents undesirable nutrients, Nutrient i (or j) denotes the content of nutrient i (or j) in each dish, DRI i is the daily recommended intake of nutrient i; and MRI j is the maximum recommended intake (MRI) of nutrient j. Since the present study focused on the Japanese population, we obtained the DRI and MRI values for all age groups in the general population according to "Dietary Intake Standards for the Japanese People (2020 Edition)" published by the Japanese Ministry of Health, Labor, and Welfare and the breakdown of age groups in the general population as of 1 October 2021 (table S2). Twenty-nine nutrients were included in the nutritional assessment, with cholesterol and salt classified as undesirable nutrients and all other nutrients as desirable. However, we cannot include in the calculation the results for all 29 nutrients but focus only on the 18 with recommended intake values in Japan. For instance, dietary guidelines generally suggest an overall protein intake value rather than a more detailed breakdown of the amino acids in proteins.

Second, different parts of the population may have specific and different dietary needs and preferences. Following established methods for developing NDS sub-indices (*99*, *101*), we calculated four sub-indices that reflect the dietary preferences of different parts of the population. The current Japanese dietary guidelines recommend a low-calorie diet for overweight and obese people, for which we calculated NDS-Eng (energy). For "responders," a low-cholesterol diet is recommended, for which we estimate NDS-Cho (cholesterol). For all groups, especially those that need to exercise or to lose weight, a diet with an adequate protein intake is recommended; therefore, we calculated the NDS-Pro (protein). Moreover, a low-salt diet is suggested for people with high blood pressure and underlying cardiovascular disease; therefore, we calculated the NDS-Sat (salt). Equations 10 to 13 provided the adjusted NDS based on the following four categories

$$\text{NDS}-\text{Eng}=\sum_{i=1}^{x}\frac{\text{Nutrient } i}{E\times\text{DRI } i}-\sum_{j=1}^{y}\frac{\text{Nutrient } j}{E\times\text{MRI } j} \tag{10}$$

$$\text{NDS}-\text{Cho}=\sum_{i=1}^{x}\frac{\text{Nutrient } i}{C\times\text{DRI } i}-\sum_{j=1}^{y}\frac{\text{Nutrient } j}{C\times\text{MRI } j} \tag{11}$$

$$\text{NDS}-\text{Pro}=\text{Cons}-\sum_{i=1}^{x}\frac{\text{Nutrient } i}{P\times\text{DRI } i}-\sum_{j=1}^{y}\frac{\text{Nutrient } j}{P\times\text{MRI } j} \tag{12}$$

$$\text{NDS}-\text{Sat}=\sum_{i=1}^{x}\frac{\text{Nutrient } i}{S\times\text{DRI } i}-\sum_{j=1}^{y}\frac{\text{Nutrient } j}{S\times\text{MRI } j} \tag{13}$$

where for each dish, E is the energy content (in kilocalories), P is the protein content (grams of protein), C is the cholesterol content (grams of cholesterol), and S is the salt content (grams of salt).

Dietary scenarios and optimization (step 4)

Meal selection often depends on many contextual factors, such as personal preferences, cultural sensibilities, and accessibility of ingredients (*64*, *102*). Although the broad-based dietary recommendations on food group categories found in major sustainable diets can provide insight into sustainable diets, they arguably do not reflect well the possible meal options in a given cultural context or cannot be translated properly into actual meal selection considering the availability of food items (e.g., different vegetable options in different climates).

Therefore, we constructed 16 sample diet scenarios consisting of the 45 dishes considered in the present study to provide better dietary choices to residents with different eating habits. For example, the "beef" scenario contains daily dishes that only combine the nine beef dishes. Ten scenarios consisted of combinations of dishes from two categories. For example, the scenario "beef-chick" contained combinations of only eight chicken- and nine beef-based dishes. While some of these combinations might be too simplistic and provided only for illustrative purposes, others correspond to viable dietary choices. Notably, the "seaf-vege" scenario essentially reflects a pescatarian diet. We identified combinations of dishes within each scenario that met the nutritional requirements of an individual as identified in the DRI for Japan, which is collected by the Ministry of Health, Labor and Welfare, Japan yearly (*103*) and provided in table S2. Considering the Japanese meal tradition, we included 200 g of a mix of grain products as a staple food that accompanies each meal. The underlying assumption on staple food is included in table S1 in the Supplementary Materials. Therefore, we can determine the number of dish combinations that meet the nutritional requirements in each scenario.

In addition, we established an optimization model to minimize the carbon footprint of dish combinations within each scenario while meeting the nutritional requirements of an individual, which can be mathematically expressed in a mixed-integer linear program to identify a healthy and sustainable diet for Japan. Through the optimization modeling process, we provided the nutritional distributions of each scenario under minimal environmental impact. The details of the mathematical model are as follows: We numbered each dish according to the type of dish (see tables S11 and S12).

The objective of the optimization model was to minimize the variance between the nutrient intake and the recommended intake value while minimizing the carbon footprint, as presented in Eq. 14

$$\min f = \sum_m \mathrm{CF}_m + \left|\sum_n (\mathrm{standard}_n - \mathrm{DN}_n)\right| \tag{14}$$

where CF_m denotes the carbon footprint of each meal (assuming that a person has three meals per day and $m = 1,2,3$) and $\mathrm{standard}_n$ refers to the DRI for nutrient type n. The first term in Eq. 14 minimizes the daily food-related carbon footprint, whereas the second term aims to reduce the nutrient intake deviation from the DRI. The upper and lower limits for the 12 nutrients (table S13) were set to varying ranges, and the DRI values were adopted as a reference to obtain the recommended diet.

In the proposed mathematical model, three constraints were considered: (i) carbon footprint equilibrium (constraint 1), (ii) nutrient intake (constraint 2), and (iii) dietary restrictions under different scenarios (constraint 3).

Under constraint 1, the total carbon footprint for each meal CF_m was the sum of the emissions from all ingredients (indirect emissions) and the cooking process (direct emissions), as presented in Eq. 15

$$\mathrm{CF}_m = \sum_{b,r} MXR_{m,b,r}\mathrm{CF}_{b,r} + \mathrm{CFS} \tag{15}$$

where $MXR_{m,b,r}$ is the dish intake binary of meal m (if one dish is consumed, the value equals 1; if not, it equals 0), $\mathrm{CF}_{b,r}$ is the carbon footprint of dish r (from both ingredients and the cooking process) in dish base b (five food type–based dishes as mentioned above), and CFS is the carbon footprint of the staple, given that 200 g of rice or noodles is generally taken as the staple food in the Japanese diet (detailed information regarding the assumptions on staple food is provided in the Supplementary Materials).

In constraint 2, we considered the balance of nutrient 12 categories. The total daily nutrient intake was the sum of the nutrient contents of the three meals, as presented in Eq. 16

$$\mathrm{DN}_n = \sum_m MN_{m,n} \tag{16}$$

where DN_n represents the daily nutrient intake for nutrient type n, $MN_{m,n}$ denotes the content of nutrient type n in meal m calculated using Eq. 17

$$MN_{m,n} = \sum_b \sum_r MXR_{m,b,r}N_{b,r,n} + \mathrm{NS} \tag{17}$$

where $N_{b,r,n}$ denote the nutrition type n of dish r in food base b, NS is the nutrition of the staple food. For each nutrient type, there were upper and lower intake limits denoted as $\mathrm{Max}N_n$ and $\mathrm{Min}N_n$, respectively, per Eq. 18

$$\mathrm{Max}N_n \geq \mathrm{DN}_n \geq \mathrm{Min}N_n \tag{18}$$

To ensure that there is no imbalance between hunger and satiety, the energy intake of each meal must be above the lowest intake level MN_L (*104*). Thus, it is required in Eq. 19, and it is necessary to consume at least one dish for each meal

$$MN_{m,1} \geq MN_L \tag{19}$$

Here, $MN_{m,n}$ denotes the content of nutrient type n in meal m (since people usually have three meals a day, here, m =1, 2, 3 refer to the breakfast, lunch, and dinner). According to the order of various nutrients in the model, the index of energy intake ranks first (see table S13). Therefore, in Eq. 19, we directly use $MN_{m,1}$ to represent the energy intake of a meal.

In constraint 3, we assumed that for a certain diet, there is no consumption of other dishes (i.e., consumption is equal to 0). For instance, in the 16 hypothetical scenarios, for single dish type-based scenarios, such as "beef," "chick," and "pork," and two dish type–based scenarios, such as "beef-chick" and "beef-pork", people cannot consume other dishes other than those included in the scenario, as per Eq. 20. In the "mixed" scenario, there was no limit to the choice of dishes

$$MXR_{m,b,r} = 0 \ (b \notin B) \tag{20}$$

where B is the specific type of diet assigned to the different allocations in the model.

For a mathematical model, any solution that satisfies all the constraints is a feasible solution. However, we aimed to develop an optimal model to determine the best feasible solution that represents the best compromise between many interrelated variables to achieve a specific goal. Therefore, for the optimization model proposed in the present study, either an optimal solution or no solution is realized in each solution process. To avoid the fact that a single optimal solution cannot effectively represent the nutritional distribution under a certain dietary scenario, we adjusted the lower limit of the objective function (i.e., increased the lower limit of the carbon footprint) to generate additional solutions.

Limitations

Despite its comprehensive approach, we need to acknowledge some of the limitations of our study that should be considered when generalizing the results. First, the only environmental impact considered in the present study considered were GHG emissions expressed as the carbon footprint. Other important environmental impacts of diets, such as land use change, water pollution, or biodiversity loss were not considered due to the lack of such data at high resolutions in Japan and the global multiregional input-output tables.

Second, the recommended nutritional intake differs among age groups, occupations, sexes, and other factors. However, in the present study these values were unified and adjusted to an average level for the entire Japanese population. In addition, for each dish included in the study we considered a single standardized recipe for that dish. However, different individuals may adjust the quantities of ingredients in a given recipe based on personal preferences, price constraints, or unavailability of certain ingredients. The actual results presented here are for an iteration of a single recipe, despite the possibility of different recipe variations for each dish. Although we strictly adhered to the original ingredient quantities, the potential randomness of individual adjustments underscores the complexity of dietary studies. Future studies and tools should consider such possibilities to enable more comprehensive and personalized nutritional advice and dietary guidance.

Thirdly, only one cooking fuel, namely LPG, was used to estimate the direct emissions associated with cooking. Although this is the most prevalent cooking fuel in Japan, there is a need to consider other cooking fuels (e.g., electricity and natural gas). Changes in cooking fuel might affect results; however, we believe the overall effect would be small considering the low direct emissions observed for all dishes compared with the indirect emissions (Fig. 1). The underlying technique is sufficiently flexible to consider other cooking fuels, including cooking fuels that might be more prevalent in other geographical contexts.

Supplementary Materials

This PDF file includes:
Figs. S1 and S2
Tables S1 to S13

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