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LETTER

An absolute environmental sustainability assessment of food

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Abstract

The food sector is a major user of land and freshwater and a source of considerable greenhouse gas (GHG) emissions. This puts pressure on Earth systems and jeopardizes the future of food production. The environmental impact of foods is well understood, but our interpretation lacks the context to judge whether those impacts are sufficiently small to describe a food as environmentally sustainable or not. In this work, we describe a metric that converts the environmental impact of foods into a quantitative environmental sustainability scale (performance-weighted environmental sustainability, PwES). Land use, freshwater use, and GHG emission impacts of common foods have been weighted by their nutritional content and normalized so that values greater than 100% are considered unsustainable. Our findings concur with the conventional wisdom that the high impact of meat is unsustainable, whereas vegetables are typically produced sustainably. Further to this, the PwES metric was used to establish rational targets for sustainable food supply and design nutritious and environmentally sustainable meal plans. It was found that without reductions to the environmental impact of food, it is very difficult to eat sustainably. A high-bread vegan diet could be found that provided minimum nutritional requirements and was environmentally sustainable.

KEYWORDS
food and health, food technology and sustainability, nutrition

1 | INTRODUCTION

The pressures on Earth systems caused by humanity have become considerable, prompting a widespread evaluation of government policies and societal practices. Agriculture is a significant contributor to global greenhouse gas (GHG) emissions and the major cause of land use change and freshwater use (Clark et al., 2019). It follows that the environmental impact of the food supply sector must be carefully managed (Jägermeyr et al., 2021; Soria-Lopez et al., 2023; Springmann et al., 2018), especially because more food is needed to accommodate the increasing global population (Gerten et al., 2020) and improve nutrition (Eastham and Creedon, 2023; Geyik et al., 2023; Stylianou et al., 2021).

To understand how to produce food in such a way that Earth systems are not changed or impaired and thus can be considered environmentally sustainable, we must be able to measure environmental impacts and interpret them with well-defined and unambiguous benchmarks. Global agricultural impacts have been estimated and placed into context with planetary boundaries (PBs). A PB defines the maximum environmental impact that can be tolerated indefinitely without a major change to the Earth system processes that support humanity's survival (Rockström et al., 2009; Steffen et al., 2015). Some PBs have been exceeded (Figure 1a; Intergovernmental Panel on Climate Change [IPCC], 2022; Steffen et al., 2015), and urgent action is needed to reduce environmental impacts.

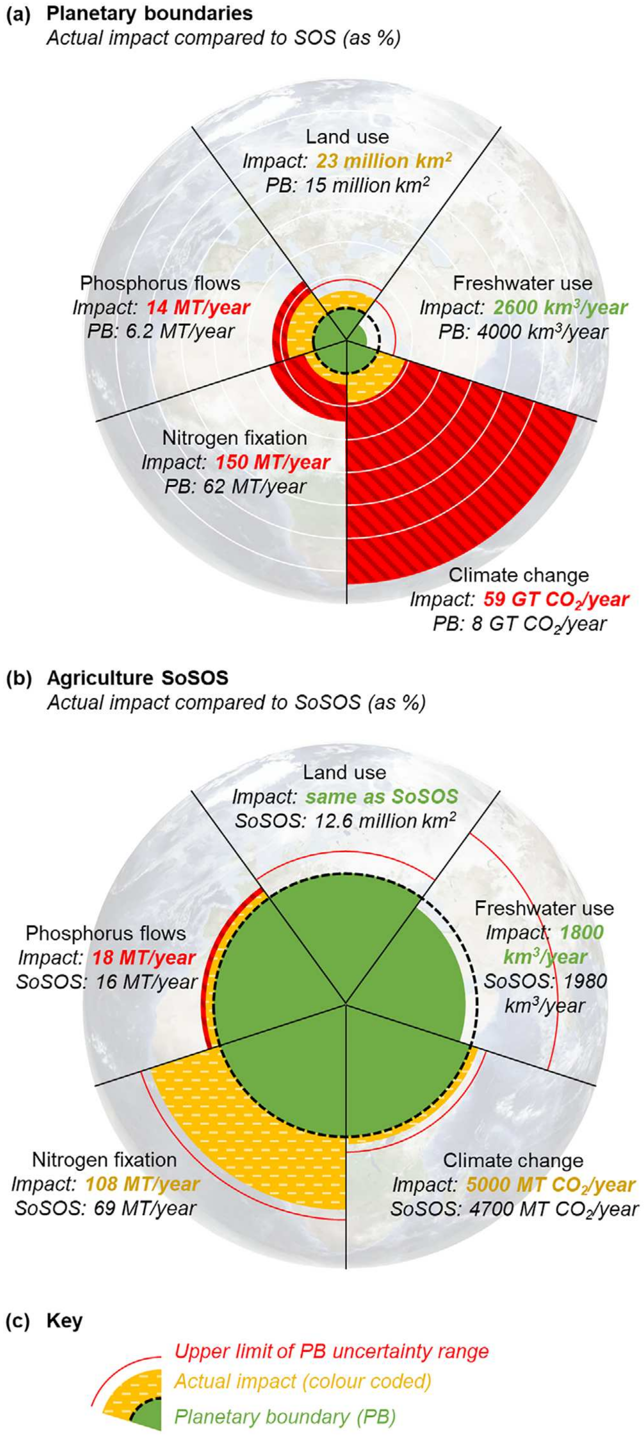

FIGURE 1 The relative magnitude of global environmental impacts and their corresponding sustainable limit: (a) planetary boundaries (PBs); (b) agricultural share of the safe operating space (SoSOS). Green (solid color) wedges represent the magnitude of sustainable impacts. Impacts that exceed the PB or SoSOS but are within the upper range of uncertainty are represented as green and yellow (dashed pattern) wedges. Unsustainable impacts are partially colored red (stripes). A key is provided as part (c) of the figure. The climate change PB is based on the mass of CO_2-equivalent emissions and Intergovernmental Panel on Climate Change (IPCC) data, not the conventional atmospheric CO_2 concentration.

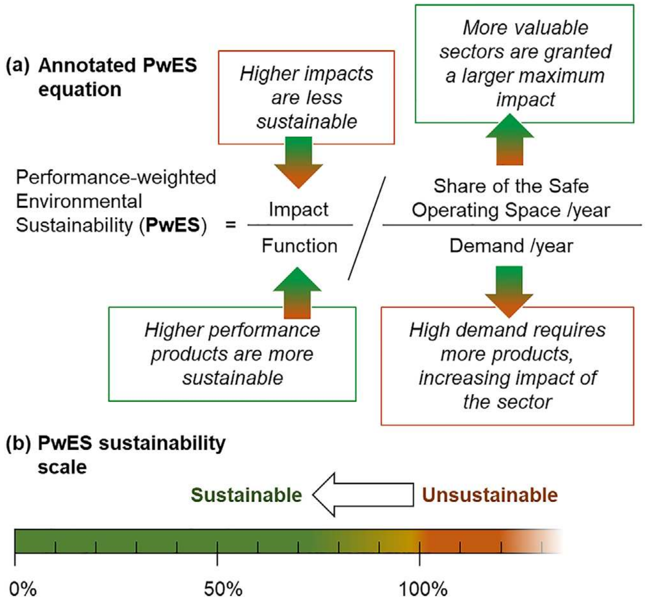

FIGURE 2 The general performance-weighted environmental sustainability (PwES) metric: (a) an annotated PwES equation. Arrows indicate whether it is desirable for values to be higher or lower: (b) the PwES scale.

A proportion of the land use, freshwater use, fertilizer use, and climate change PBs can be reserved for agricultural practices, known as a share of the safe operating space (SoSOS; see Figure 1b; Springmann et al., 2018). The actual environmental impact of agriculture can then be compared to the SoSOS in an "absolute" sustainability assessment (Ryberg et al., 2018), which can be downscaled further to analyze regional activities (Bjørn et al., 2020; Chandrakumar et al., 2019).

Although the environmental impacts of individual foods have been calculated (Clark et al., 2022; Frankowska et al., 2020), a measure of "absolute" sustainability is difficult to rationalize at this scale. Life cycle assessment (LCA) mid-point indicators (e.g., the quantity of GHG emissions per calorie) do not describe sustainability precisely, nor do they establish a uniform basis for comparing different impact categories. Alternatively, the performance-weighted environmental sustainability (PwES) metric (Figure 2a) analyzes the environmental impacts of products in the context of a maximum sustainable limit (Sherwood, 2022). The PwES metric is a product-level "absolute" sustainability indicator, previously applied to the case study of water use by washing machines (Sherwood, 2022). Instead of a traditional functional unit (as found in LCA indicators), the function of a product is normalized by demand for that function. Demand is based on consumption within the designated geographical and temporal scope. Concerning food, demand is based on dietary intake and food waste, for example, food supply to the consumer. Products that satisfy a greater proportion of demand have lower (superior) PwES values. Reducing demand also improves PwES values. In this work, PwES was adapted to evaluate the sustainability of foods using nutrition as the function variable. An innovative approach was developed to attribute each environmental impact across different functions (energy, protein, fiber, and portions of fruit and vegetables) and make PwES appropriate for describing foods.

If PwES exceeds 100%, the product is determined as unsustainable with respect to the impact category under assessment (Figure 2b). The results are unitless, making it possible to compare the sustainability of different environmental impacts (and different products) on a like-for-like basis. Rational, evidence-based environmental impact targets have been hard to justify at the product level, but PwES has been used here to establish maximum impact values for the production and preparation of individual foods, which then act as sustainability targets. Feasible technological advances can also be evaluated, as can changes to diets, as are described subsequently in this work.

2 | METHODS

2.1 | Scope

The environmental impacts of foods consumed in the United Kingdom have been analyzed for the present case study. Data for the year 2019 was used because this represents the most recent complete dataset without the anomalies of the COVID-19 pandemic. Freshwater use and CO_2-equivalent emissions data and their corresponding SoSOS are farm to fork in scope. This includes agriculture, food transportation (including packaging), food manufacturing, wholesaling and retailing (including storage and refrigeration), and meal preparation (cooking). Infrastructure and labor are excluded from the assessment. Land use was reduced in scope to agriculture only. These principles are consistent with the environmental impact data sources (Frankowska et al., 2019a, b; Poore and Nemecek, 2018; Springmann et al., 2018) and have been translated to the definition of the PB allocations (Figure 3). Please refer to the literature data sources for additional details on the scope of the assessment that has been adopted (Frankowska et al., 2019a, b; Poore & Nemecek, 2018).

2.2 | Assessment variables

Values for the PBs were obtained from the primary literature (Rockström et al., 2009; Steffen et al., 2015). The standard PBs and agricultural SoSOS for land use and freshwater use were used, expressed as m^2 and L/year, respectively (provided in Supporting Information S1). The exception was the climate change PB, which was changed to units of mass of CO_2 (eq.) per year to be compatible with impact data (IPCC, 2022). A climate change PB of 2350 MT CO_2-eq. /year has been suggested (Petersen et al., 2022), but this is less than deemed sustainable for global agriculture alone at 4700 MT CO_2-eq./year (Springmann et al., 2018). To resolve this contradiction, the IPCC emissions projections for "net zero" were used, that being 8000 MT CO_2-eq./year (with an uncertainty range of 0–16,000 MT CO_2-eq./year; IPCC, 2022). This is the quantity of CO_2 emissions that shall be offset by 2050 to meet "net-zero" targets.

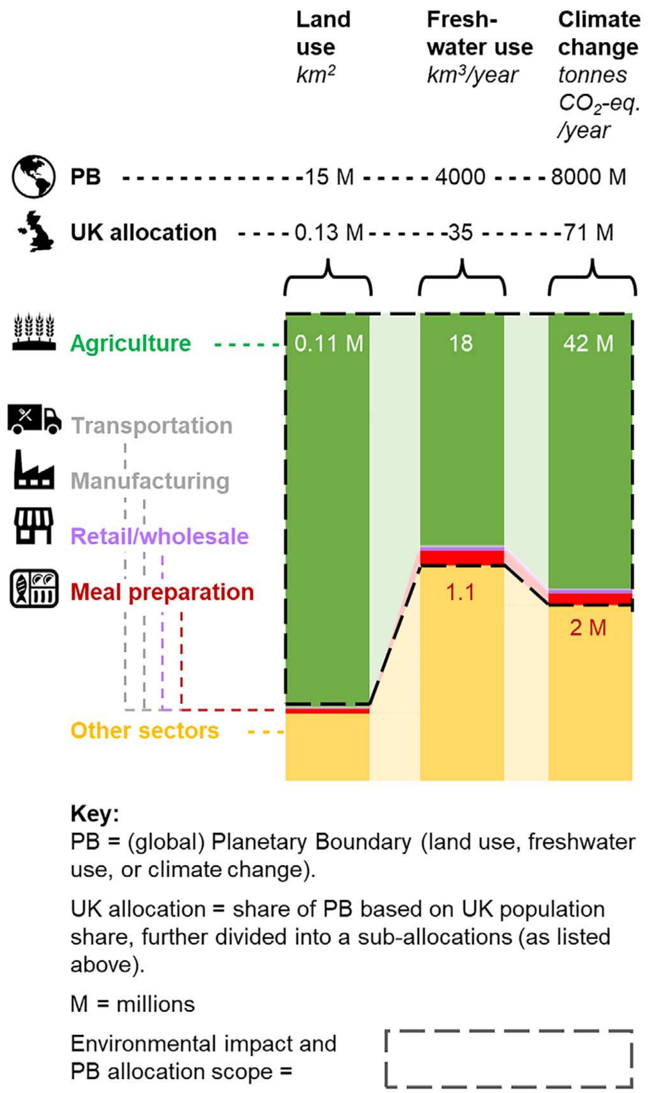

FIGURE 3 Assessment scope for land use, freshwater use, and climate change impacts, also corresponding to the planetary boundary allocation in each category (which are stated numerically). Transportation, manufacturing, and retail/wholesale allocations are barely visible in the graphic.

The PB allocation for global agricultural practices (the SoSOS) was obtained from Springmann et al. (2018). UK agriculture was allocated a share of the global PBs for agriculture on a capita basis (population is represented by P in subsequent equations), as is common practice (Equation 1; Ryberg et al., 2020). Population data was obtained from FAOSTAT (Food and Agriculture Organization of the United Nations [FAO], 2019a) and the United Nations [UN] (2019). Allocations for other UK sectors were derived from their relative contribution to the UK economy (excluding agriculture). The total gross value added (GVA) for the United Kingdom (Office for National Statistics [ONS], 2022) was supplemented by the contribution of unpaid services to the UK economy (ONS, 2018). The equivalent value of household meal preparation in GVA terms was added to the GVA generated by the UK catering industry to represent food preparation (Equation 2). The GVA of food transportation, food manufacturing, wholesaling, and retailing was then added to represent the full UK food supply chain, farm to fork (Equation 3). These calculations were applied to the land use, freshwater use, and climate change PBs (Rockström et al., 2009; Steffen et al., 2015), to obtain the corresponding SoSOS of the UK food supply chain. Note that for land use, impact data is limited in scope to only agricultural land, and so the SoSOS is derived for agriculture only (as in Equation 1). Alternative SoSOS allocation methods were also evaluated (Hjalsted et al., 2021). Interactive data with which to explore each PB downscaling method is provided as Supporting Information S1:

$$SoSOS_{UK}^{agriculture} = SoSOS_{global}^{agriculture} \cdot \frac{P_{UK}}{P_{global}} \quad (1)$$

$$SoSOS_{UK}^{meal\ preparation} = \left(PB_{global} - SoSOS_{global}^{agriculture}\right) \cdot \frac{P_{UK}}{P_{global}} \cdot \frac{GVA_{UK}^{catering} + GVA_{UK}^{home\ meal\ preparation}}{\left(GVA_{UK}^{normal} + GVA_{UK}^{unpaid\ services} - GVA_{UK}^{agriculture}\right)} \quad (2)$$

$$SoSOS_{UK}^{food\ supply} = SoSOS_{UK}^{agriculture} + SoSOS_{UK}^{food\ transport} + SoSOS_{UK}^{food\ manufacture} + SoSOS_{UK}^{food\ sales} + SoSOS_{UK}^{meal\ preparation} \quad (3)$$

The SoSOS for UK food supply was then separated into the contributing functions of energy (in the form of calories), protein, fiber, and portions of fruit and vegetables (to represent micronutrients, where one portion is 80 g of a fruit or vegetable), and other non-food agricultural products. In order to do so, the nutrition of each foodstuff was converted into a nutritional unit (NU, per kg) after dividing by demand for that nutrition (calories, protein, fiber, or portions of fruit and vegetables). The example of broccoli calories is provided in Equation (4). Demand for nutrition is based on the United Kingdom in 2019, including the nutrition included in edible food waste, and was calculated from food production data provided by FAOSTAT (FAO, 2019a). To evaluate meals, the sum of the nutrition (e.g., total calories per meal) is used in Equation (4) without further modification. Nutritional information was sourced from the USDA "FoodData Central" database (United States Department of Agriculture [USDA], 2019):

$$NU_{broccoli}^{energy}\ (per\ kg) = \frac{Energy}{Energy\ demand} = \frac{340\ kcal\ per\ kg}{3373\ kcal\ per\ person\ per\ day} = 0.1\ per\ kg \quad (4)$$

The gross production value (V), via FAOSTAT (FAO, 2019b), of all foods was distributed among their different nutritional functions using the relative magnitude of the NUs. The example of broccoli calories is given in Equation (5) (the equivalent calculation for meals is the same). By summation of all foods, the economic value of foods attributable exclusively to energy provision in the form of calories is obtained (Equation 6). The same process was repeated for protein, fiber, and portions of fruit and vegetables. For foods without nutritional data, the average for that class of food was used (categorized into grains, roots, sugar crops, oil crops, pulses, nuts, fungi, animal products, vegetables, and fruit). The value of non-food products was combined to give the value of the UK non-food agricultural sector:

$$V_{broccoli}^{energy}\ (\$) = V_{broccoli}\ (\$) \cdot \frac{NU_{broccoli}^{energy}\ (per\ kg)}{NU_{broccoli}^{energy}\ (per\ kg) + NU_{broccoli}^{protein}\ (per\ kg) + NU_{broccoli}^{fibre}\ (per\ kg) + NU_{broccoli}^{fruit/veg}\ (per\ kg)} \quad (5)$$

$$V_{UK\ food}^{energy}\ (\$) = \sum_{k=food\ group}^{n=all\ foods} V_{k}^{energy}\ (\$) \quad (6)$$

The gross production value of food calories, protein, fiber, and portions of fruit and vegetables were used to assign a proportion of the UK food supply SoSOS (for land use, freshwater use, and climate change) to each of the nutritional categories. The energy (calories) example is shown in the following equation:

$$SoSOS_{UK\ energy}^{food\ supply} = SoSOS_{UK}^{food\ supply} \cdot \frac{V_{UK\ food}^{energy}\ (\$)}{V_{UK\ food}\ (\$)} \quad (7)$$

Land use, freshwater use, and GHG emission impacts (mean, 10th percentile, median, and 90th percentile) were sourced from the work of Poore and Nemecek (2018). This dataset has a scope starting at agriculture and ending at UK retail (inclusive). The exception is land use, which is limited to agriculture. Alternative datasets are also available in Supporting Information S2 (Frankowska et al., 2019a, b; Springmann et al., 2018). The impact of meal preparation cooking methods (specifically GHG emissions) was sourced from Frankowska et al. (2020). The water use associated with meal preparation was calculated from food packaging instructions and cooking apparatus instructions (i.e., a food steamer). Additional freshwater use associated with water supply (i.e., leaks) and electricity generation was also included, based on a previously published methodology (Sherwood, 2022).

The subdivision of an environmental impact (e.g., the GHG emissions associated with producing and eating broccoli) into individual contributions toward each nutritional function is performed with NU and V. The example for the GHG emissions (CO_2-eq./kg) attributed to the calories provided from eating broccoli is provided in Equation (8). To allocate the impact of a meal among each nutritional function, the sum of the environmental impacts and the sum of the meal's nutrition are used in the following equation:

$$Impact_{broccoli}^{energy}(GHG\ emissions,\ CO_2eq./kg) = \frac{Impact_{broccoli}\ (CO_2eq./kg) \cdot NU_{broccoli}^{energy}\ (per\ kg) \cdot V_{UK\ food}^{energy}(\$)}{\left(NU_{broccoli}^{energy} \cdot V_{UK\ food}^{energy}\right) + \left(NU_{broccoli}^{protein} \cdot V_{UK\ food}^{protein}\right) + \left(NU_{broccoli}^{fibre} \cdot V_{UK\ food}^{fibre}\right) + \left(NU_{broccoli}^{fruit/veg} \cdot V_{UK\ food}^{fruit/veg}\right)} \quad (8)$$

The PwES calculation is performed as stated in Equation (9) on a calorie basis, using the mean GHG emission impact of steamed broccoli as an example. The result is the same if protein or fiber or portions of fruit and vegetables are used as the nutrition category (see Supporting Information S3) and is equally applicable to meals and any combination of foods. The exception is when a foodstuff does not supply a nutritional function. Meat products are allocated zero environmental impact in the categories of fiber and portions of fruit and vegetables, for instance, but PwES calculated in terms of energy or protein will be equal:

$$\begin{aligned} &\text{Climate change } PwES^{energy}_{broccoli} \\ &= \frac{Impact^{energy}_{broccoli}\ (CO_2eq./kg)}{SoSOS^{food\ supply}_{UK\ energy}\ (CO_2eq./year)} \Big/ \frac{Function\ \ (kcal/kg)}{Demand\ \ (kcal/year)} \end{aligned} \tag{9}$$

2.3 | Alternative metric formats

Alternative analyses using only energy (calories) to describe the function of food, and a micronutrient division of nutrition were also prepared (Supporting Information S4). When only considering energy to describe the function of food, the entire environmental impact is used, as is a SoSOS for food supply as a whole (Equation 10). Micronutrients were selected from the "Nutrient Rich Food Index" (NRF9): protein, fiber, vitamin A, vitamin C, vitamin E, calcium, iron, potassium, and magnesium (Drewnowski, 2010). Demand for these micronutrients was calculated from food production quantities and the nutrition content of those foods (Supporting Information S5). Otherwise, the PwES calculation works on the same basis as the standard macronutrient version by extending the impact allocation (Equation 11). Magnesium was generally used to perform the micronutrient variant of the PwES calculation because it is present in the majority of foods (Equation 12), although for oils, vitamin E was used:

$$\begin{aligned} &\text{Climate change } PwES_{broccoli} \\ &= \frac{Impact\ \ (CO_2eq./kg)}{SoSOS^{food\ supply}\ (CO_2eq./year)} \Big/ \frac{Function\ \ (kcal/kg)}{Demand\ \ (kcal/year)}. \end{aligned} \tag{10}$$

$$Impact^{magnesium}_{broccoli} = \frac{\cdot NU^{magnesium}_{broccoli}\,(per\ kg)\cdot V^{magnesium}_{UK\ food}\,(\$)}{\begin{aligned}&\left(NU^{protein}_{broccoli}\cdot V^{energy}_{UK\ food}\right)+\left(NU^{fibre}_{broccoli}\cdot V^{fibre}_{UK\ food}\right)+\left(NU^{vitaminA}_{broccoli}\cdot V^{vitaminA}_{UK\ food}\right)+\left(NU^{vitaminC}_{broccoli}\cdot V^{vitaminC}_{UK\ food}\right)\\ &+\left(NU^{vitaminE}_{broccoli}\cdot V^{vitaminE}_{UK\ food}\right)+\left(NU^{calcium}_{broccoli}\cdot V^{calcium}_{UK\ food}\right)+\left(NU^{iron}_{broccoli}\cdot V^{iron}_{UK\ food}\right)+\left(NU^{potassium}_{broccoli}\cdot V^{potassium}_{UK\ food}\right)+\left(NU^{magnesium}_{broccoli}\cdot V^{magnesium}_{UK\ food}\right)\end{aligned}} \tag{11}$$

$$\text{Climate change } PwES^{magnesium}_{broccoli} = \frac{Impact^{energy}_{broccoli}\ (CO_2eq./kg)}{SoSOS^{food\ supply}_{UK\ energy}\ (CO_2eq./year)} \Big/ \frac{Function\ \ (kcal/kg)}{Demand\ \ (kcal/year)} \tag{12}$$

2.4 | Error analysis

An uncertainty analysis and a sensitivity analysis are provided in Supporting Information S6. The sensitivity analysis was performed using the methodology described by Ryberg et al. (2018). All the variables were perturbed by 10% by default in the sensitivity analysis.

The visualization of the uncertainty analysis was performed by randomly generating a cumulative probability distribution (between 0 and 1) for each fundamental variable in the PwES calculation. This was repeated 500 times. A normal distribution was used to describe the variation in the nutritional content of foods (calories, protein, and fiber), demand for nutrition (calories, protein, fiber, and portion of fruit and vegetables), the economic distribution of total food production value onto different nutrients, and population (United Kingdom and global). A logarithmic normal distribution was used for environmental impacts. To account for leap years, the number of days in the year was assumed to be 366 with 0.25 probability. This is necessary in the conversion of daily food demand to annual demand. The portions of fruit and vegetables in 1 kg of an applicable foodstuff were fixed at 12.5 (each portion being 80 g). The uncertainty of the SoSOS for agriculture and the nonagricultural sectors in the food supply chain was based on equally likely values within the (large) error ranges provided in literature sources (Springmann et al., 2018; Steffen et al., 2015). Note that the estimations in the FAOSTAT (FAO, 2019a) database relate to supply, not consumption, and a large standard deviation has been applied to the uncertainty analysis (Supporting Information S6; Del Gobbo et al., 2015).

3 | RESULTS

3.1 | Performance-weighted environmental sustainability analysis

The PwES metric requires a quantitative definition of a product's function and demand for that function. The primary function of food is to provide nutrition, which is multi-faceted and can be defined in different ways (Clark et al., 2022; Saarinen et al., 2017). Here, four parallel functions (collectively referred to as macronutrients for convenience) were defined: energy (in terms of calories), protein, fiber, and portions of fruit and vegetables. Consumption of these macronutrients (including household food waste) was used as the corresponding demand category (e.g., grams of protein consumed per year). The PwES value of any given food must be the same regardless of which macronutrient

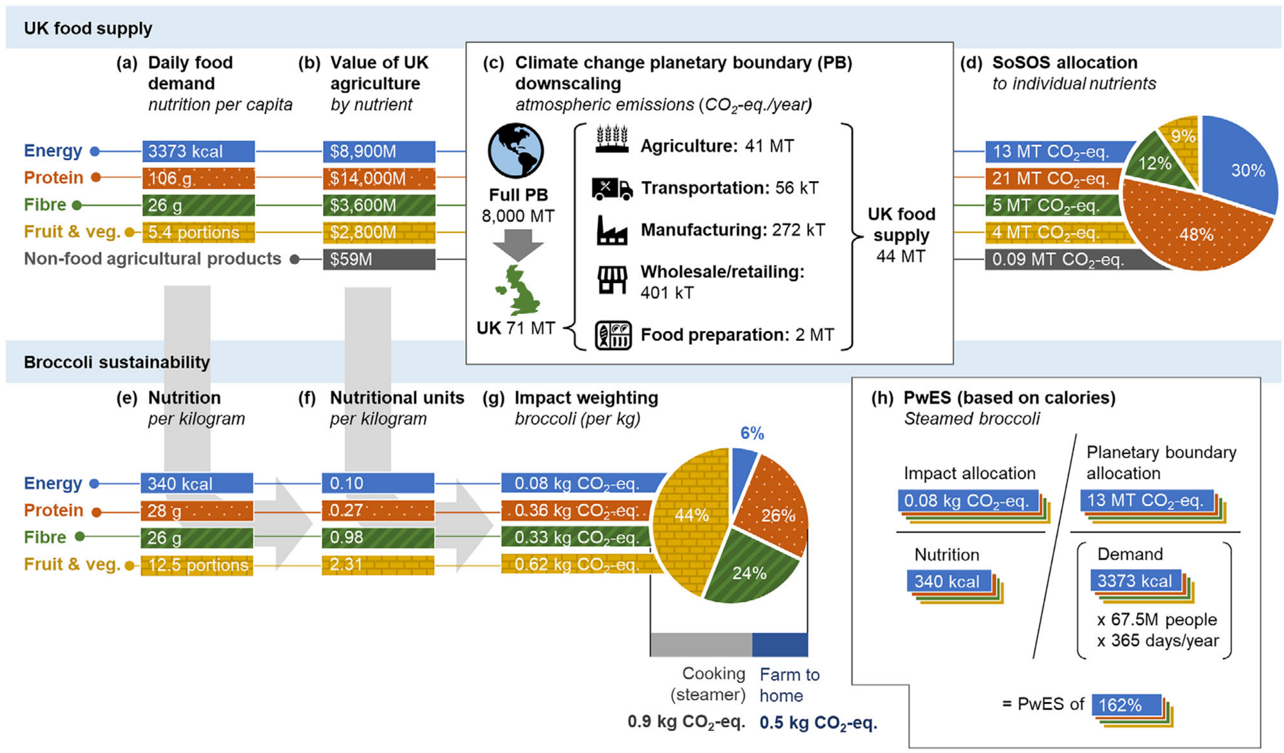

FIGURE 4 A worked example of a performance-weighted environmental sustainability (PwES) calculation, describing the climate change impact of producing and consuming broccoli in the United Kingdom: (a) demand for food per capita in the United Kingdom in 2019; (b) the gross production value of UK agriculture in 2019 separated into contributions toward producing different macronutrients; (c) calculation of the UK food supply climate change share of the safe operating space (SoSOS), downscaled from the corresponding planetary boundaries; (d) the division of the SoSOS by macronutrient; (e) the nutritional content of 1 kg of broccoli; (f) nutritional units for broccoli calculated between panels a and e; (g) the separation of the greenhouse gas (GHG) emissions associated with broccoli consumption into allocations by macronutrient; (h) the PwES calculation for broccoli GHG emissions, based on energy (calories). Energy is represented by the solid blue sections, protein in speckled orange, fiber in striped green, and portions of fruit and vegetables in the yellow brick pattern.

is chosen to describe it (Supporting Information S3), and so environmental impacts and their respective SoSOS (e.g., land use, freshwater use, or GHG emissions) were subdivided into allocations towards the provision of each macronutrient. This is a notable shift from the conventional LCA mid-point indicator, where one function (the functional unit in LCA terminology, e.g., calories) is used to justify the entire environmental impact, despite foods offering diverse nutritional benefits.

A worked example of the climate change impact of producing and consuming broccoli is provided in Figure 4. The assessment is based on the UK food supply in 2019. Food demand is given in Figure 4a (Supporting Information S5). The gross production value of food consumed in the United Kingdom, $29.7 billion (Supporting Information S7; FAO, 2019b), was allocated by macronutrient (Figure 4b; see Equations 5 and 6). Hence, 30% of the value of all agricultural products was attributed to the production of energy (calories), whereas almost half can be attributed to protein due to the high value of (protein-rich) animal products.

The climate change SoSOS for UK food supply was calculated as summarized in Figure 4c (Supporting Information S1). The PBs and the global agricultural SoSOS were downscaled to a UK-scale SoSOS by population. The full SoSOS for UK food supply and preparation was completed with allowances for food transportation, manufacturing of processed foods, retail, and meal preparation. The relative GVA of the industry sectors was used to determine an SoSOS, as is standard practice (Equations 1–3; ONS, 2022). In the case of home food preparation, an estimate of GVA, calculated as if home cooking was paid employment and thus generated revenue, was used based on government estimates (ONS, 2018). The total UK food sector climate change SoSOS was calculated at 44 MT CO_2-eq./year (Figure 4c). Once multiplied by the relative value of food production by macronutrient (Figure 4b), an allocation of the SoSOS for individual macronutrient was achieved (Figure 4d). Consequently, 13 MT CO_2-eq. is the maximum sustainable quantity of GHG emissions that can arise annually as a consequence of creating food calories for UK consumption (Figure 4d and Equation 7). The total UK food sector SoSOS representing land use is 110,000 km^2 and 19 km^3/year for freshwater use.

For 1 kg of broccoli, the function by macronutrient is given in Figure 4e. Dividing the nutritional content by demand (Figure 4a) creates NUs (see Figure 4f and Equation 4) that, in combination with the gross production value of UK agriculture (Figure 4b), were used to derive subdivisions of the total environmental impact by macronutrient (Figure 4g). Therefore, the distribution of the total environmental impact of a food onto its calorie content, protein, fiber, and portions of fruit and vegetables is based on the quantity of those macronutrients in the food, and the economic value of those macronutrients. Farm-to-retailer, the GHG emissions of broccoli have a mean average impact of 0.5 kg CO_2-eq./kg (Poore & Nemecek, 2018). Alternative data for fruits and vegetables can be found in Supporting Information S2 (Frankowska et al., 2019a, b). Cooking broccoli in a steamer on an electric oven hob creates additional emissions of 0.9 kg CO_2-eq./kg (Frankowska et al., 2020). The total impact of 1.4 kg CO_2-eq./kg translates into just 0.08 CO_2-eq./kg to generate the calories in broccoli according to Equation (8). A much more significant allocation of 0.62 CO_2-eq./kg represents the impact of producing the portions of fruit and vegetables embodied in broccoli (one portion is 80 g).

The PwES calculation for broccoli climate change impact is shown in Figure 4h (and Equation 9). This version uses calories for the function and demand variables. Demand has been converted from daily per capita calorie demand into national demand for food energy. The result of 162% indicates that the typical GHG emissions associated with producing broccoli and cooking it with an electric hob steamer for UK consumption is unsustainable. A reduction of total GHG emissions to 0.9 kg CO_2-eq./kg (farm to fork) would bring the PwES value down to 100%.

The premise that the function of food can be described as a combination of energy (calories), protein, fiber, and portions of fruit and vegetables was tested with alternative methods (data in Supporting Information S4). First, energy was applied as the sole function. The result is that high-energy foods receive lower PwES values, with vegetable oils benefiting the most. Conversely, low-calorie foods have higher PwES values compared to the standard approach. For example, the climate change PwES of tomatoes increased from 356% to 2194% when energy was the only function considered. Second, a multivitamin approach was also assessed, consisting of the following functions: protein, fiber, vitamin A, vitamin C, vitamin E, calcium, iron, potassium, and magnesium (Drewnowski, 2010). Foods lacking in vitamins or minerals are penalized with this methodology, as are starchy and high-sugar foods (including fruits) because calories are not included as a function. The PwES values of rice, pork, apples, grapes, and refined sugars all at least doubled. This system favored foods with a diverse nutritional profile, especially vegetables, for which PwES values improved (i.e., decreased). The climate change PwES for steam-cooked broccoli is reduced significantly from 162% to 51%, meaning it is now sustainable under this interpretation. Carrots and soymilk PwES values were also more than halved. Ultimately, the four-function PwES model was ultimately chosen because the energy-only approach favored high-calorie (and potentially unhealthy) foods, whereas the micronutrient NRF9 approach tended to favor low-impact vegetables that can often be produced sustainably anyway.

3.2 | Sustainability of foods

The sustainability of foods with respect to land use, freshwater use, and GHG emissions is presented in Figure 5 and Supporting Information S2. Environmental impacts above the line marking 100% within Figure 5 are unsustainable. The environmental impact prior to cooking (from agriculture, retail, etc.) has been expressed as the mean average, and additionally, the 10th, median, and 90th percentiles are shown (Poore & Nemecek, 2018). This data was added to the impact of preparing the food (freshwater use and GHG emissions). Typical cooking methods were assumed (listed and editable in Supporting Information S2; cooking impacts by cooking technique sourced from Frankowska et al., 2020). A summary of PwES values according to cooking device and technique is given in Supporting Information S8.

Animal products use unsustainably large areas of land, especially lamb and beef and eggs and dairy (Figure 5a). The land use PwES values, even at the 10th percentile, are an order of magnitude greater than what can be considered sustainable. Conversely, the land use required to produce nonleguminous plant-based foods is, on average, considered sustainable. Legumes such as peas and lentils need to be produced with half the current average land use to meet the designated sustainable limit. Sugars and vegetable oils also require unsustainably high areas of land; these foods suffer for their lack of nutritional diversity, for the absence of fiber or protein is penalized within the PwES metric. Conversely, the typical functional unit of calories benefits calorie-dense foods in standard LCAs.

The way in which nutrition is considered by the PwES metric has an important influence on the perceived sustainability of the food. Potatoes, for instance, require the same average area of land per kilogram as orange production (0.9 m^2-year) but potatoes have a mean average PwES of 78%, whereas for oranges, it is 47%. This is because oranges count toward the recommended daily portions of fruit and vegetables, but potatoes do not. This more than compensates for the higher calories per kilogram that potatoes have compared to oranges. Bread has a similar land use PwES (76%) as potatoes (78%), but bread requires considerably more land to produce (3.9 m^2-year per kilogram). Bread has more calories, protein, and fiber per kilogram than potatoes, and so land use up to 4.4 m^2-year per kilogram would be considered sustainable (resulting in a PwES $\leq$100%) for the benefit (i.e., nutrition) obtained from bread. For potatoes, the maximum sustainable land use is much lower at 1.1 m^2-year per kilogram (in the context of this case study) because of the relatively low nutrient density of potatoes compared to bread.

The freshwater use impact of foods is sustainable for fruits and vegetables on average (Figure 5b). For all other products with a mean PwES greater than 100%, there are examples of sustainable production and consumption for all foods within the 10th and 90th percentiles, except for farmed salmon. The mean freshwater use for the production of beef, lamb, and dairy is unsustainable, but the median freshwater use translates to a PwES value below or close to 100%. Cooking water is insignificant compared to the contribution of agricultural freshwater use to PwES (only for potatoes is the contribution of cooking water visible on the scale given in Figure 5b, shown as a gray bar).

Sustainability assessments commonly report stress-weighted freshwater use values. The stress-weighted freshwater use PwES values are provided in Supporting Information S2 (Poore & Nemecek, 2018). The stress-weighting of freshwater use was performed using the methodology of Boulay et al. (2018), resulting in significantly larger volume-eq.

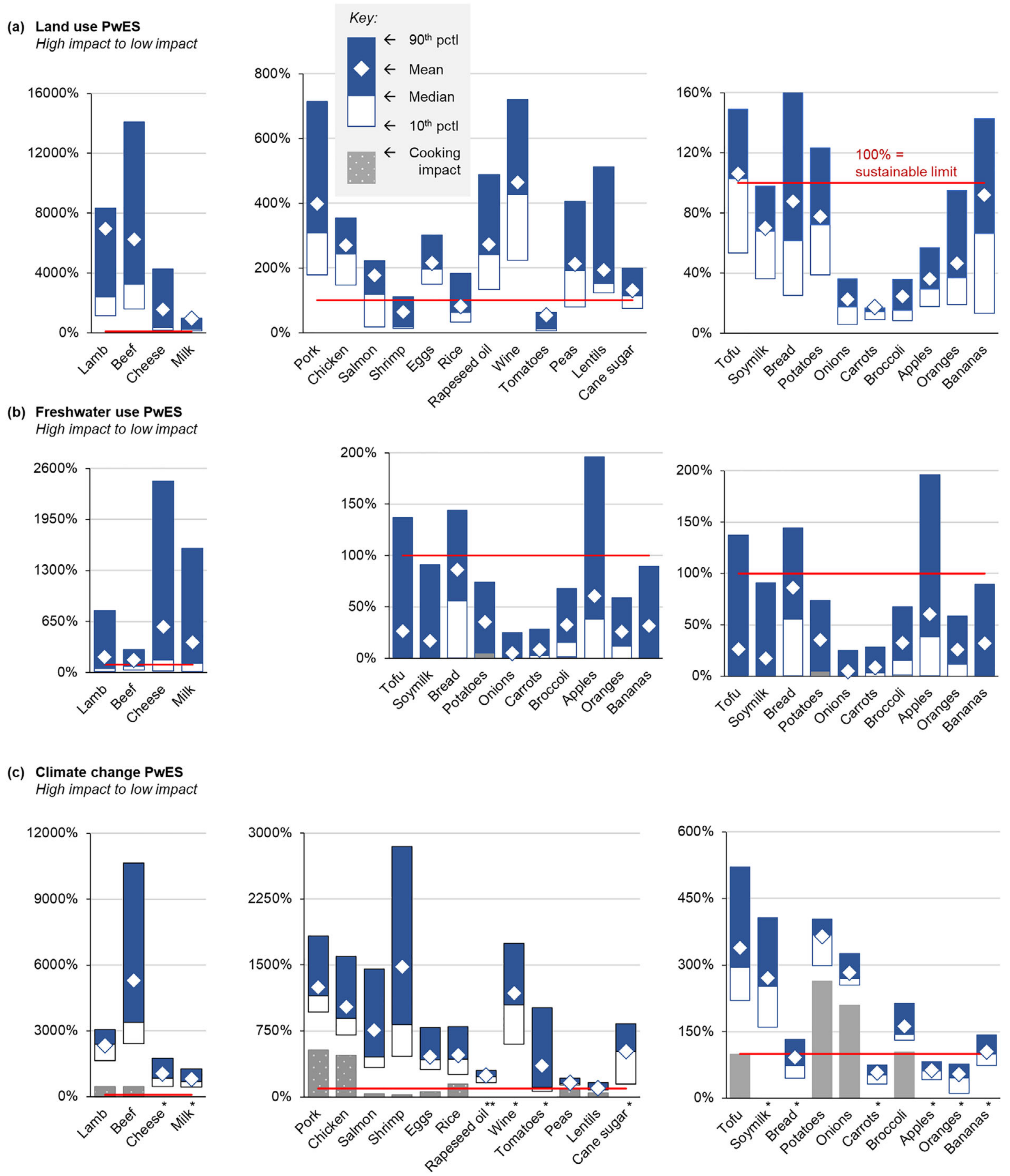

FIGURE 5 The sustainability of UK food supply (a) land use, (b) freshwater use, and (c) greenhouse gas (GHG) emissions according to performance-weighted environmental sustainability (PwES). Foods are grouped by the general magnitude of their environmental impacts. Mean average values are shown as diamond datapoints. Gray speckled columns represent the typical cooking impact. Data range resulting from different agricultural methods and locations as shown in key. The PwES = 100% line is shown in red. *These foods are assumed to be consumed raw (or in the case of bread, not recooked or toasted at home). **Oils are assumed to be raw, for dressing foods, or if used in cooking, the impact of cooking the oil is wholly allocated to the food(s) cooked in the oil. Meats were assumed to be roasted, eggs, rice, peas, lentils and potatoes boiled, salmon and broccoli steamed, shrimp, tofu, and onions fried.

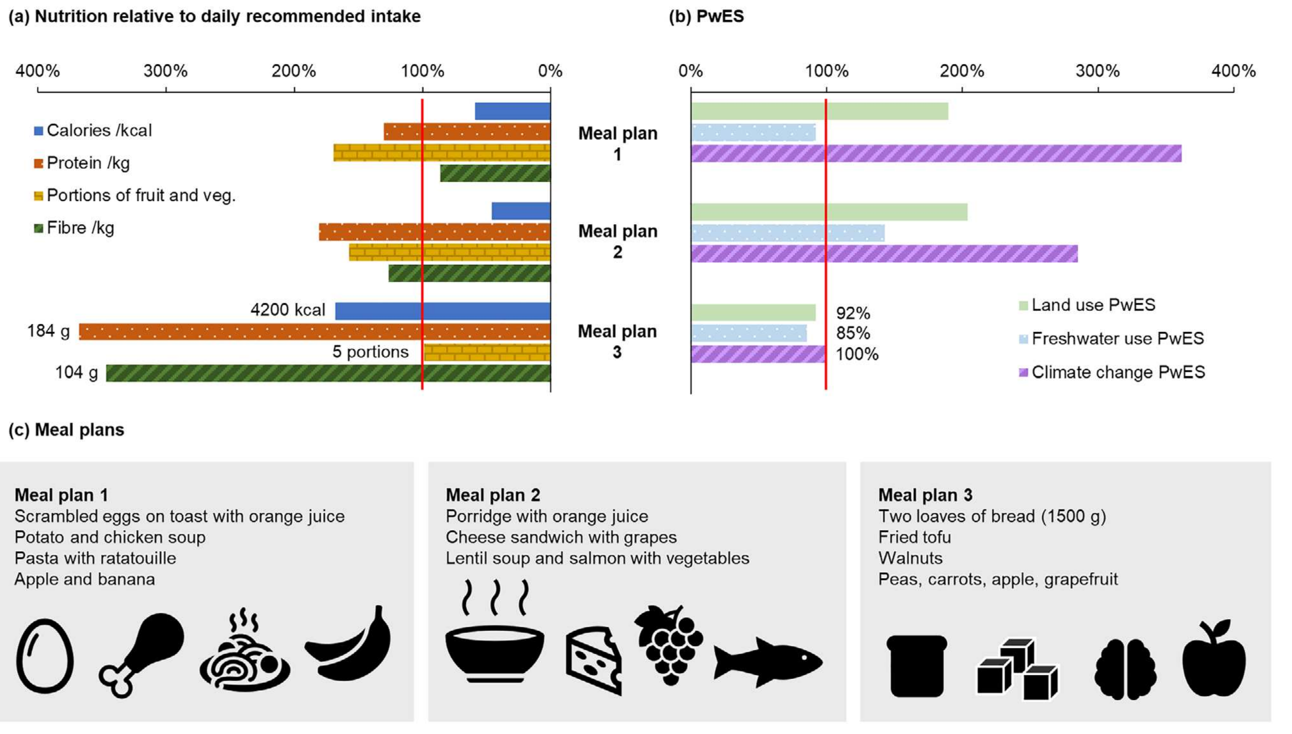

FIGURE 6 The nutritional content and performance-weighted environmental sustainability (PwES) values of three daily diets: (a) nutrition as a percentage of the recommended adult daily intake of 2500 kcal, 50 g protein, five portions of fruit and vegetables, and 30 g of fiber. Energy represented as solid blue bars, protein in speckled orange, fiber in striped green, and portions of fruit and vegetables in yellow brick pattern: (b) PwES values. Land use PwES represented as solid green bars, freshwater use PwES as speckled blue bars, climate change PwES as purple stripes; (c) composition of each day of meals.

than the actual volume of water used, and as such, no animal products, fruit, or vegetables could be considered sustainable. For example, the standard freshwater use PwES of broccoli is 33%, which increased to a stress-weighted equivalent of 2218% (mean average including imports). UK produce has lower stress-weighted freshwater use PwES values compared to the average (which includes imported foods) due to the moist temperate climate (Frankowska et al., 2019a, b). However, the United Kingdom can only produce 60% of its total food demand (by value) with the remainder coming from imports (Department for Environment Food & Rural Affairs [DEFRA], 2022).

The GHG emissions associated with food on the UK market are almost always unsustainable according to their climate change PwES values (Figure 5c). The meats of ruminant animals (sheep and cattle) are the least sustainable of the dataset. Only bread and some fruits (apples and oranges) can be considered having a sustainable climate change impact. Carrots, if eaten raw, are also sustainable in this respect (PwES = 57%), but upon cooking, the cumulative emissions in CO_2-eq. are unsustainable (PwES values up to 610%; see Supporting Information S8).

4 | DISCUSSION

The PwES assessment of foods is generally consistent with related studies, emphasizing the high environmental impact of meat and indicating that plant-based foods are more sustainable. However, the PwES metric goes further by quantifying environmental sustainability, offering a means to establish maximum acceptable environmental impacts, rationalize best practice, and evaluate diet choices in a robust manner. There are two key strengths to the PwES methodology that make it worthy of consideration to supplement conventional LCA (or footprint reporting, etc.) studies. First, however, LCA mid-point indicators report environmental impact as a function of mass or calories (McLaren et al., 2021), or sometimes as a combination of nutritional content (Drewnowski, 2010). This standardized method of reporting is familiar and easy to understand. The alternative approach of PwES reports the impact attributable to each aspect of a food's nutritional content (Figure 4g). The PwES methodology places higher accountability on the dual aspirations of low environmental impact and high nutrition. For example, the GHG emissions of producing and cooking broccoli are 0.42 kg CO_2-eq./100 kcal with a PwES of 162%. Cane sugar has average GHG emissions of only 0.08 kg CO_2-eq./100 kcal but a larger climate change PwES of 521%. The diverse nutritional content of broccoli justifies a higher environmental impact, albeit one that is still unsustainable. Second, by normalizing impact data with the SoSOS, and deriving a functional unit from demand for nutrition, the data is comparable between impact categories and directly relates to sustainability, with scores below 100% indicative of a sustainable product. External benchmarks are unnecessary. This means the climate change PwES of broccoli (162%) can be sensibly compared to the freshwater use PwES of apples (60%), with the latter determined to be sustainable and the former unsustainable. The equivalent LCA indicators, 0.42 kg CO_2-eq./100 kcal versus 0.35 L/100 kcal, respectively, make sense individually, but the units are different, which prevents a direct comparison.

The total environmental impact of daily meal plan can be evaluated with an aggregate PwES value, making it feasible to balance high environmental impact foods with low-impact foods for a nutritious and sustainable diet. No adjustment to the PwES calculation is needed when changing from a single food item to meals other than to recalculate the impact weighting (following the same principle as in Figure 4g) based on the nutrition of the meal as a whole. Three daily meal plans have been assessed (Figure 6). The source data for Figure 6 is provided in the Supporting Information, where the methodology is shown, and custom meals can also be designed. Meal plans 1 and 2 are based on UK government nutritional recommendations (Food Standards Scotland, 2023). Environmental sustainability was not considered in the selection of ingredients. Both are low in calories with an abundance of fruit and vegetables, yet unsustainable (although the freshwater use impact of meal plan 1 has a PwES below 100%).

In order to provide a person's minimum daily nutritional requirements (2000–2500 kcal, 50 g protein, 30 g fiber, and five portions of fruit and vegetables; Public Health England, 2016), and not exceed a PwES of 100% in each impact category, a vegan meal plan was devised (meal plan 3). The low environmental impact of bread permitted such a meal plan (Espinoza-Orias et al., 2011; Kulak et al., 2015; Notarnicola et al., 2017; Poore & Nemecek, 2018). Meal plan 3 of Figure 5 provides over 80% of a person's daily dietary fiber, protein, and calories from bread alone. Disease prevention and other health and social benefits are attributed to the consumption of bread (De Boni et al., 2019; Gil et al., 2011; Sajdakowska et al., 2019), but the very large quantity of bread in meal plan 3 resembles the diet of medieval farm laborers (Dyer, 1988). Contemporary bread consumption is actually in decline (Lockyer and Spiro, 2020), implying that meal plan 3 is not in keeping with modern eating habits and is unlikely to be adopted as a realistic diet. Furthermore, gluten intolerance limits the choice of breads for over 1% of the UK population (National Health Service [NHS], 2023). Globally, some geographical areas are not suited to wheat production, and culturally, other starchy foods are the foundation of regular diets. Rice is a prominent example. To enable diversity and cultural acceptability of any proposed sustainable diet, and simply to enjoy a greater variety of foods than meal plan 3 provides (Figure 6), a reduction in environmental impacts is necessary (Supporting Information S9). For animal products to be considered sustainable, the reduction in GHG emissions needed is far greater than the optimistic 10%–15% range projected by Springmann et al. (2018) (farm emissions only). Transportation accounts for an average of 26% of fruit and vegetable GHG emissions (Frankowska et al., 2019a, b), which are often produced sustainably anyway, and the impact of transportation becomes less significant for higher impact foods (Our World in Data, 2023; Poore & Nemecek, 2018). This means that future reductions to the impact of transport (and other energy-intensive actions such as refrigeration) will only have a small influence on the sustainability of our food supply. Increased renewable energy in the electricity mix will make a considerable difference to the impact of many foods where the GHG emissions of cooking are the major contributor to the climate change PwES value (generally roasted or baked foods). Nevertheless, the most optimistic reductions in GHG emissions across the food supply chain will only reduce climate change PwES values below the sustainable threshold for those foods with PwES values already only marginally above 100% (e.g., peas; see Supporting Information S9). Boiled rice, for example, has its mean average climate change PwES reduced from 480% to 220%, an impressive improvement but still not sustainable within the parameters of this assessment. This reemphasizes the importance of the demand variable in PwES. Widespread reductions to food waste, overconsumption, and diets with less red meat are needed in combination with technological changes to create a sustainable food supply sector (as explored in Figure 6 and supplemented with Supporting Information S9).

Although the authors believe PwES greatly simplifies and improves the communication of environmental sustainability, there are some barriers to its implementation. The error associated with the quantification of the PBs is a large source of uncertainty (see Supporting Information S6 for an uncertainty analysis). Some PBs have a range of uncertainty greater than 80% of the default value (Steffen et al., 2015). The PwES calculation is also sensitive to the accuracy of population estimates given that the downscaling of PBs is performed per capita, and food demand data availability is variable among regions (sometimes with large errors; Del Gobbo et al., 2015). However, for a given food and impact category, the environmental impact has the strongest correlation to the resulting PwES value (being the most sensitive variable). Despite being in the family of "absolute environmental sustainability assessments" (Bjørn et al., 2019), the definition of "function" in the PwES metric is subjective, with alternatives provided in Supporting Information S4. Describing food function in terms of energy (calories), protein, fiber, and portions of fruit and vegetables suits a UK assessment because it aligns with national guidelines for a healthy diet (Public Health England, 2016). There are also different approaches to the downscaling of PBs (Supporting Information S1).

Overall, it has been demonstrated that the PwES metric can be translated to foods and provides definitive numerical information to establish a quantitative measure of environmental sustainability. When compared to regional food sustainability assessments (Bjørn et al., 2020; Lucas et al., 2021), the product-level focus of PwES is relatable to consumers, and specific impact targets are more obvious. Thus, the PwES assessment of foods and meals can offer a systematic approach to understanding and acting upon environmental impacts, simplifying sustainability reporting, and removing the barriers that previously hindered comparisons between different products and impact categories.

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CONFLICT OF INTEREST STATEMENT

The authors confirm that they have no conflicts of interest to declare for this publication.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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