Determining the absolute sustainability of products with case studies on laundry and food production

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Abstract

In this work, a new metric called ‘Service-weighted Product Level Absolute Sustainability’ is proposed as a numerical indicator to determine if a product is sustainable. The service offered by a product was found to be crucial to normalize its environmental impact and permit comparisons between products. Service-weighted Product Level Absolute Sustainability is demonstrated here with examples of water use for laundry and food production. The maximum justifiable environmental impact of these products has been calculated based on their performance, i.e., the quantity of clothes washed or nutritional content. Now the environmental impact of products can be rationalized as either sustainable or unsustainable, informing sustainable choices by manufacturers as well as consumers.

Keywords

Agriculture, Environmental impact, Indicator, Planetary boundaries, Sustainability, Water.

Introduction

The deterioration of the environment undermines efforts to sustain essential services and habitable living conditions. Accordingly, environmental sustainability is now embedded into many aspects of governance, business, and society. Tools for monitoring sustainability include the Environmental Performance Index,[1] and the Sustainable Society Index.[2] National or global scale multi-criteria indicators such as these may introduce emission targets to normalize an impact category, but do not typically provide a well-defined absolute ecological limit to those environmental impacts. Therefore, while it is possible to identify an environmentally preferable practice, whether it is sustainable or not is unclear.

The proposal of planetary boundaries has introduced absolute limits on human activities, including water use, land use, and pollution.[3,4] A planetary boundary defines the tipping point of an Earth system process, beyond which the ecosystem becomes unstable with potentially disastrous consequences. The best-known planetary boundary is the safe limit to atmospheric CO_2 concentrations with respect to climate change. Other examples relevant to this work are provided in Table 1. The contribution of natural processes is subtracted from a planetary boundary to give the 'safe operating space' for humanity. Some planetary boundaries define exclusively anthropogenic activities and so the safe operating space is equivalent to the planetary boundary in those instances.

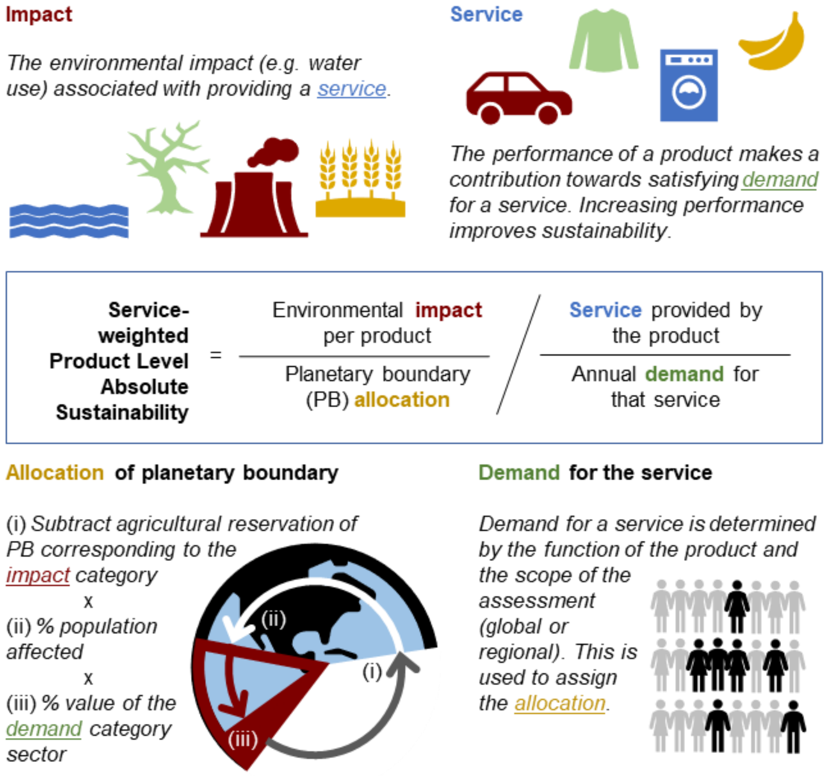
Table 1. The magnitude of planetary boundaries. Uncertainty ranges are shown in brackets. Tg is terragrams (10^{12} g).

Planetary boundary	Global scale.[3,4]	Safe operating space.[5]	Agricultural allocation.[7]
Freshwater use (km^3/year)	4000 (4000-6000)	4000	1980 (780-3190)
Land use change (million km^2)	18.2 (18.2-24.2)	18.2	12.6 (10.6-14.6)
Industrial nitrogen fixation (Tg/year)	62 (62-82)	62	Not applicable
Nitrogen fertilizer application (Tg/year)	Not defined	Not defined	69 (52-113)
Phosphorus fertilizer application (Tg/year)	6.2 (6.2-11.2)	6.2	16 (8-17)
Climate change	350 (350-450) ppm CO_2	278 ppm CO_2	4700 (4300-5300) Tg CO_2-eq./year

The scale and ambition of the planetary boundary concept is suited to inform international policies,[6] but they can also be divided into allocations to suggest a maximum environmental impact for different activities. This ‘downscaling’ exercise has been performed for agriculture by Springmann et al.[7] Note that the sustainable limit to fertilizer use was actually increased compared to the full planetary boundaries (Table 1), suggesting a larger environmental impact can be tolerated than previously thought.

Downscaling the planetary boundaries and combining with life cycle assessment (LCA) is the basis of absolute environmental sustainability assessments.[8,9] For example, the annual environmental impact of a municipal water company has been interpreted relative to a calculated maximum permissible impact.[10] An allocation of each planetary boundary was determined based on the population being supplied with water and the household expenditure on this utility. The resulting ‘share of safe operating space’ reports if the allocated share of a planetary boundary for a specific purpose has been exceeded. It was found in this example that some impacts were sustainable (e.g. relating to stratospheric ozone depletion) but many were not (e.g. climate change indicators). Algunaibet et al. investigated the environmental impact of the USA power industry in a similar way but concentrated their efforts on understanding three future scenarios.[11] Bjørn et al. identified the environmental impact of laundry detergent manufacturing and use by introducing geographically resolved allocations of the planetary boundaries.[12] The absolute sustainability of each process in the life cycle was then calculated using an economic allocation, and by doing so revealed that producing the raw materials from vegetable oils was responsible for the majority of the economic-weighted land use and biogeochemical flow impacts (i.e. fertilizer use). The carbon emissions of the New Zealand horticultural sector have also been evaluated with an absolute sustainability assessment.[13] The allocation of the global carbon budget to this sector was based on its historical share of emissions (globally) and then one of 4 methodologies was applied to attribute it exclusively to New Zealand. Of which, only the economic allocation suggested the foods (apples, kiwifruit, wine) were sustainably produced.

In environmental sustainability assessments, the societal need satisfied by services and products is typically defined by their monetary value. The primary aim of this work is to show that the environmental sustainability of products can be interpreted in a way that is relatable to how we use them, thus the function and performance (i.e. service) of a product can be represented as a variable in absolute sustainability assessments. Combining environmental impacts with the societal benefit obtained from the function of a product reveals how the choices made in the design of products and the implementation of services defines their sustainability. Specifically, the ratio between the service provided by a product and demand for that service, compared to the ratio between its environmental impact and the maximum permissible impact, can be used to indicate if a product is sustainable. The resulting metric is called Service-weighted Product Level Absolute Sustainability (Fig. 1) and abbreviated to SPLASH. It is a unitless indicator and can be calculated for any environmental impact category with a corresponding planetary boundary. Any value over 100% is regarded as unsustainable.



Impact

The environmental impact (e.g. water use) associated with providing a service.

Service

The performance of a product makes a contribution towards satisfying demand for a service. Increasing performance improves sustainability.

Service-weighted Product Level Absolute Sustainability = (Environmental **impact** per product / Planetary boundary (PB) **allocation**) / (**Service** provided by the product / Annual **demand** for that service)

Allocation of planetary boundary

(i) *Subtract agricultural reservation of PB corresponding to the impact category*
x
(ii) *% population affected*
x
(iii) *% value of the demand category sector*

Demand for the service

Demand for a service is determined by the function of the product and the scope of the assessment (global or regional). This is used to assign the allocation.

Fig. 1. A new absolute sustainability assessment format using product performance to interpret environmental impact. This generic example is for non-agricultural products. See Note S1-S7 for more information.

Service can be defined as the benefit received from the intended purpose of a product. Increased performance or an extended product lifespan improves the service that is obtained from that product. Annual demand corresponds to the collective receipt of a service by a given population, and so it is defined by consumer behaviours. Various future market scenarios can be analyzed with Service-weighted Product Level Absolute Sustainability to predict necessary improvements in technology or determine a sustainable level of consumption for a given population.

Metrics describing products have previously incorporated an efficiency scale to justify resource use,[14] but do not directly measure sustainability. The European Commission's Product Environmental Footprint (PEF) methodology will introduce a standardized LCA approach designed to permit fair comparisons between products within the same category.[15] However, PEF is not an absolute sustainability assessment and comparisons between dissimilar products with different functions are not valid. This is because a LCA reports environmental impacts relative to a functional unit (e.g. the grams of CO_2 emitted by a vehicle per kilometre). Service-weighted Product Level Absolute Sustainability normalizes product performance by demand for that service, and so eliminates specific functional units for different products. This achieves valid comparisons between unrelated products.

As is true of 'share of safe operating space' calculations, a proportion of the planetary boundaries (specifically the safe operating space) must be allocated to the demand category relevant to the product in question. Appropriate methods are debated,[16,17] but the basis of relative economic value is typically applied. In this work, a significant proportion of relevant planetary boundaries has been reserved for agriculture, as was previously determined by Springmann et al.,[7] and only then is the remainder allocated to non-agricultural sectors according to their economic value (Fig. 1).

The case studies in this work have been chosen because equivalent regional assessments have been previously published,[5,12] and therefore the results can be compared. The absolute sustainability of freshwater use for laundry and producing tomatoes are evaluated here on the basis of a single wash cycle and 1 kilogram of tomatoes respectively. The scope is defined so that the result is the same for the whole operational lifespan of the washing machine or if a single tomato from that harvest is considered.

Results

Water use by washing machines

The first demonstration of Service-weighted Product Level Absolute Sustainability describes the freshwater use of washing machines. This case study was chosen to permit a comparison with the first 'share of safe operating space' assessment,[5] in which it was calculated that the 34.3 billion wash cycles performed in the EU each year consumes 1.55 km^3 of water. The global freshwater use planetary boundary is 4000 km^3/year,[4] of which an allocation can be reserved for EU clothes washing by multiplying the proportion of the global population resident in the EU by the gross value added (GVA) generated by the laundry sector (specifically detergents, corresponding to 0.28 km^3 of freshwater per year). Accordingly, the resulting 'share of safe operating space' is 554%, considerably exceeding the sustainable threshold of 100%.

We now compare the regional assessment to the Service-weighted Product Level Absolute Sustainability of a single washing machine, accounting for its water efficiency (Fig. 2). The service provided by a washing machine can be considered as a single wash cycle instead of the cumulative number of wash cycles over its lifespan because a washing machine consumes water as a linear function of its use. The water use of washing machines was sourced from manufacturer specifications. [18,19,20] It was assumed all water is bluewater (surface water and groundwater) to match the planetary boundary definition. The washing machine water use quoted in other assessments falls between that of the products used in this work (33 L and 72 L per wash).[5,21] The amount of water required to manufacture a washing machine has been excluded as it was previously shown to be minimal,[5] but for consistency the GVA contribution to the allocation of the freshwater planetary boundary is for clothes washing services only and excludes the GVA generated from manufacturing washing machines (see Table S1-2 and Fig. S2).

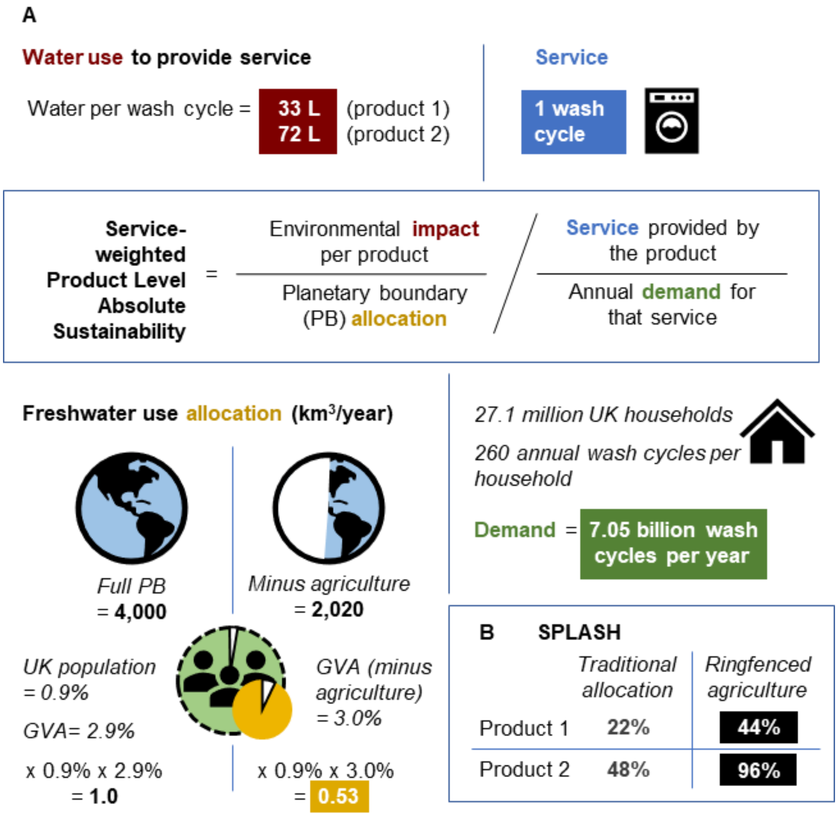


Fig. 2. The freshwater use Service-weighted Product Level Absolute Sustainability of UK washing machines. (A) Metric variables and allocations of the freshwater planetary boundary to match the scope of demand (with and without ringfencing agriculture). (B) Service-weighted Product Level Absolute Sustainability of two washing machines with different water efficiencies.

To calculate demand for wash cycles, it was assumed a 6 kg load household washing machine is used 260.1 times a year, as obtained from a previous life cycle assessment.[22] The annual demand for UK wash cycles was calculated by multiplying the number of households by the clothes washing frequency stated above (see Table S3). This was in preference to using an estimate of the number of operational household washing machines so that launderette users contribute to the total demand for laundry.

Service-weighted Product Level Absolute Sustainability emphasizes the importance of service, and commensurately the value of unpaid household services in the UK have been valued and a GVA assigned for the year 2016.[23] Laundry accounts for 2.9% of this expanded GVA measure (see Table S1). The quantities of water required by agriculture are much higher than would be allocated according to GVA, and so not to impair food production an allocation of freshwater use can ringfenced for agricultural purposes.[7] The contribution of laundry to UK (expanded) GVA after excluding food production is 3.0% (of the non-agricultural economy), meaning 0.53 km^3 of freshwater is available as the sustainable limit to satisfy annual UK laundry demand by this measure (Fig. 2A).

The Service-weighted Product Level Absolute Sustainability of laundry, adjusted to UK demand according to population,[22] is calculated as 44%, rising to 96% for more water intensive washing machines (Fig. 2B). After considering the increase in UK population since 2016, the latter washing machine represents the limit of a sustainable product with Service-weighted Product Level Absolute Sustainability recalculated as 100% (retaining the same economic allocation, see Table S15). A washing machine that consumes more than 72 L of freshwater per wash is therefore unsustainable with respect to water use in the UK market. The discrepancy with the regional analysis by Ryberg et al. is mostly caused by the choice of economic allocation (compared in Fig. S1).[5] The present analysis is more proportionate with the overall evaluation of Steffen et al.,[4] who calculate current freshwater use globally is about two-thirds of the sustainable limit.

Contemporary food production

The second case study addresses food production. As alluded to, agriculture is a major water user, both in scale and importance. The service provided by food is not straightforward to define, and its different nutritional benefits must be taken into account. Energy in the form of calories, protein, and portions of fruit and vegetables have been considered here as the basis of the service provided by food. A worked example for water used to grow tomatoes is given in Fig. 3.

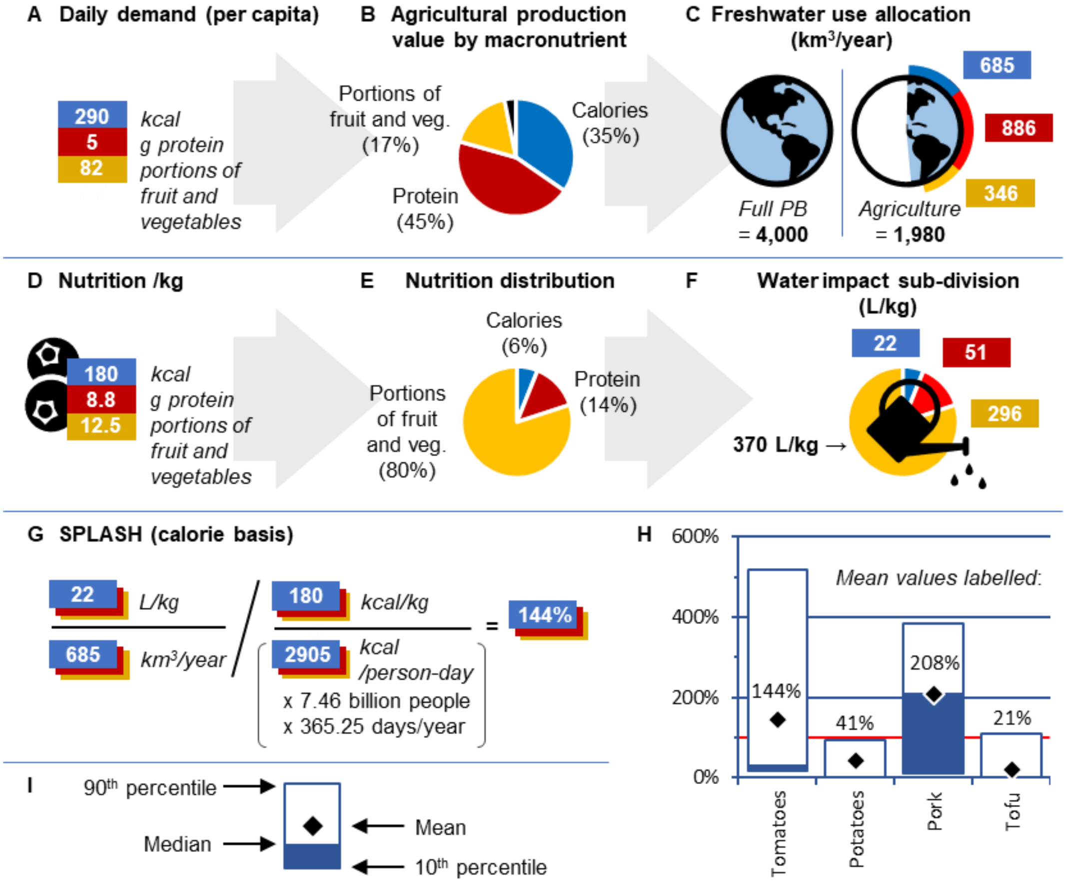


Fig. 3. The calculation of freshwater Service-weighted Product Level Absolute Sustainability to produce tomatoes. (A) Contemporary food demand. (B) Division of agricultural production value into macronutrients, normalized by nutritional demand (non-food products account for 3%). (C) Sub-division of the freshwater use planetary boundary according to macronutrient as defined by agricultural production value. (D) Nutritional content of a kilogram of tomatoes. (E) The relative nutrition of tomatoes normalized by nutritional demand and weighted by agricultural production value of macronutrients. (F) Water impact of tomato production allocated according to macronutrient. (G) Service-weighted Product Level Absolute Sustainability (SPLASH) calculated on a calorie basis. (H) Ranges of Service-weighted Product Level Absolute Sustainability for tomatoes and additional foods, with key (I).

The planetary boundary reservations for food production,[7] were split into contributions towards the provision of different macronutrients. To do so, the energy (kcal), protein (grams) and equivalent portions of fruit and vegetables (one portion is 80 g) in 1 kg of farmed foodstuffs was sourced from the USDA ‘FoodData Central’ database.[24] Food production data (by mass) was sourced from FAOSTAT,[25] to establish the daily demand for food (inclusive of waste) per capita (see Fig. 3A and Table S4). The nutritional content of every foodstuff was then divided by the daily demand (per capita) for each respective macronutrient (see Table S4 and Section 2.2) to calculate nutritional units (NU, per kg). The global gross production value of a foodstuff,[25] was multiplied by its NU to assign a monetary value to the provision of each macronutrient. The summation of all foodstuffs attributed 35% of each planetary boundary reserved for agriculture to energy (calories). The provision of protein was assigned 45% and fruit and vegetables 17% (Fig. 3B). The remaining 3% is the sum of the production value generated from non-foods. A summary is given as Table S8 and provided in full in the supplemental data file. This resulting weighting of planetary boundary agricultural allocations is shown for freshwater use in Fig. 3C and for other planetary boundaries in Table S6.

Land use and water use impacts were sourced from the work of Poore and Nemecek because mean, median, and percentile data was made available and land use was also reported inclusive of grazing pasture.[26] Fertilizer data was not used from this source as it is expressed in terms of emissions, while the corresponding agricultural planetary boundaries are expressed in terms of fertilizer application, but note that conversion factors are available.[27] Instead, Springmann et al. was the source of contemporary mean fertilizer application (by mass of nitrogen or phosphorus).[7]

The environmental impact incurred during food production must also be distributed proportionally according to the relative provision of energy, protein, and portions of fruit and vegetables. Taking the example of water use to produce tomatoes, nutritional content (Fig. 3D) was converted into NU and weighted with the same economic allocation used for the planetary boundaries (Fig. 3E). This was then used to assign a share of the environmental impact to each macronutrient (Fig. 3F). The procedure of weighting the environmental impact of each product and the planetary boundaries with NU ensures the Service-weighted Product Level Absolute Sustainability is the same regardless of what macronutrient is chosen as the demand category. The exception is when a foodstuff does not supply a macronutrient. Meat products are allocated zero environmental impact in the category of portions of fruit and vegetables for instance, but the Service-weighted Product Level Absolute Sustainability calculated in terms of energy or protein demand are equal. Tomatoes produced with the mean average water use of 370 L/kg,[26] have a Service-weighted Product Level Absolute Sustainability of 144% with respect to freshwater use (Fig. 3G). By this measure, the maximum sustainable quantity of freshwater that can be used for the production of one kilogram of tomatoes is 257 litres. Water use to produce tomatoes, potatoes, and pork are tabulated in Table S5.

Water use in food production varies considerably, and when Service-weighted Product Level Absolute Sustainability is applied to specific products (e.g. tomatoes produced in different regions with different farming practices) it can differentiate between sustainable and unsustainable sources of the same foodstuff. For instance, the median freshwater use to produce tomatoes is sustainable. Figure 3H also shows the freshwater use Service-weighted Product Level Absolute Sustainability of potatoes, pork, and tofu (from soybeans), including the range between the 10th and 90th percentile.[26] A significant amount of tomatoes and pork are produced unsustainably, but the majority of potato and tofu production requires sustainable quantities of irrigation water. The sustainability of water use and land use for a further 27 foods are analyzed in Fig. S3-4, revealing unsustainably high water use for most meat products and rice production in particular.

A regional assessment evaluating the water use to produce tomatoes is available in the literature and provides a means of comparison with the service and demand interpretation of environmental sustainability developed in this work.[12] Bjørn et al. used temporally as well as spatially resolved water demand and the value of tomato farming to the regional economy as methods to assign a sustainable volume of water use to this industry.[12,21] In some regions, they found freshwater use for producing tomatoes was more than 5000% of the indicated sustainable maximum.[12] The planetary boundary allocation used in this work is based on the more generous suggestion by Springmann et al. that recognizes agriculture requires intensive use of water, land, and fertilizers.[7] The water scarcity of a region and its seasonal variation in rainfall would be compatible with Service-weighted Product Level Absolute Sustainability assessment if both the time-dependent variables (demand and the planetary boundary allocation) were consistent with one another. However, limited data availability restricts the application of this more thorough, time-resolved method.[12]

Future food production

Service-weighted Product Level Absolute Sustainability can also be used to evaluate future food production, and interpret the benefit of different actions taken to improve the sustainability of agricultural practices. Figure 4 explores four scenarios for the year 2050, calculating if the environmental impact incurred to produce tomatoes, potatoes, and pork is sustainable (further examples are provided in the supplemental materials). Technological advances that enable a reduction to water use, land use, nitrogen and phosphorus fertilizer application were previously determined by Springmann et al.[7] In addition, different food production scenarios for the year 2050 were also considered. Firstly, it was assumed there will be no change to food demand per capita, and so global demand increases proportionally with population. A second future food production scenario was designed to reflect lower consumption of animal products and an average nutritional intake equivalent to minimum daily dietary requirements (i.e. an average of 2000 kcal, 50 g protein, and 5 portions of fruit and vegetables per capita) but also factoring an additional 17.75% food waste factor across all macronutrients (see Table S4). This food surplus was chosen to provide leeway in providing sufficient nutrition and to match energy (kcal) availability to that suggested by Gerten et al. as possible to achieve within planetary boundaries.[28] This future scenario diet is based on some of the suggestions by Springmann et al.,[7] although they considered food waste separately.

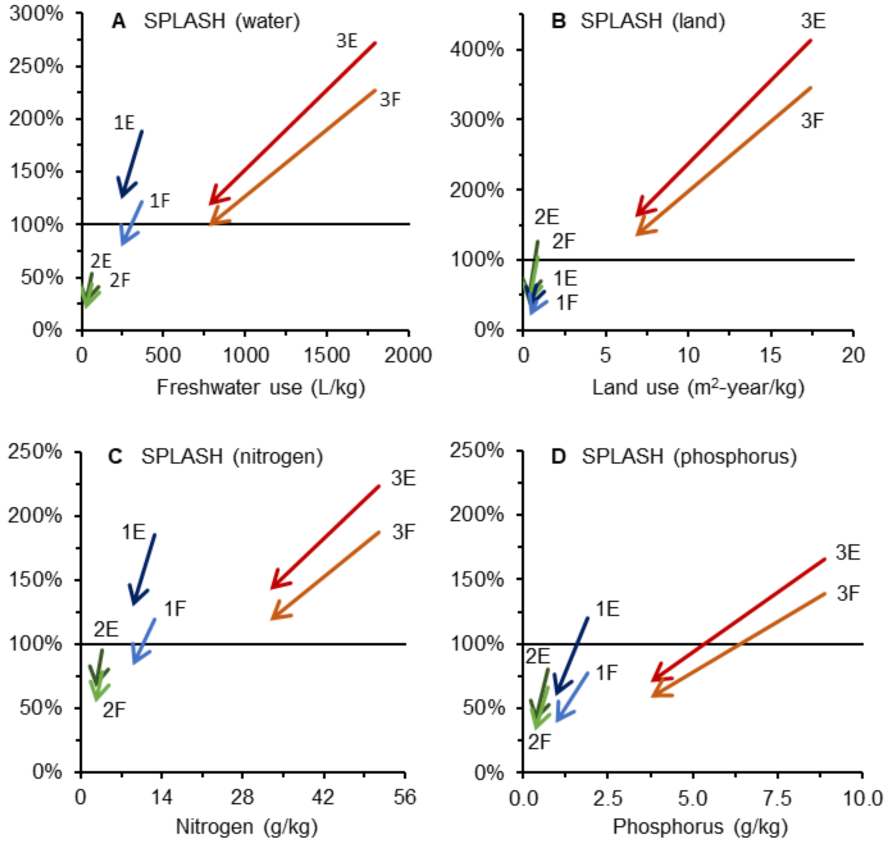


Fig. 4. Mean environmental impacts and Service-weighted Product Level Absolute Sustainability for tomatoes (1, blue arrows), potatoes (2, green arrows), and pork (3, red and orange arrows) in 2050. Arrows start at mean

impact and end at reduced mean impact after introducing technological advances, applied to an extrapolation of current diets (labelled 'E') and an alternative flexitarian diet (labelled 'F'). Service-weighted Product Level Absolute Sustainability (SPLASH) calculations are shown for (A) freshwater use, (B) land use, (C) nitrogen fertilizer application, (D) phosphorus fertilizer application.

The economic allocation in the future food production scenarios was unchanged (from that shown in Fig. 3B) when the daily demand per capita was maintained. The 2050 reduced diet scenario uses the alternative daily nutritional demand in Table S4 to produce the NU, and accordingly the division of the planetary boundary agricultural allocation between macronutrients was adjusted (Table S7). The gross agricultural production value in 2050 was estimated in line with the dietary changes in Table S4 and scaled proportionally with the estimated population change to 2050 (see supplemental data file). To do so it was assumed the relative monetary value of foodstuffs is the same in 2050.

For tomatoes and pork to be produced (on average) with sustainable amounts of water in 2050, both improved technology and diets are required (Fig. 4A). Land use (Fig. 4B, an expanded chart is available as Fig. S6) and nitrogen fertilizer application (Fig. 4C) for producing pork remains unsustainable regardless of what interventions are enacted. Phosphorus recycling could make tomato and pork production sustainable (Fig. 4D), while the quantities of fertilizer needed to produce potatoes will remain sustainable (on average) to 2050 without changing diets or needing technological advances in farming. Current day fertilizer use has already transgressed planetary boundaries,[4] which is reflected by the high Service-weighted Product Level Absolute Sustainability of most foods in this respect (see Fig. S5 for more examples).

Discussion

Through these first demonstrations, Service-weighted Product Level Absolute Sustainability has been shown to provide an absolute measure of product sustainability that had previously remained elusive. This calculation can be applied to any product that provides a quantifiable service. Comparisons between products are permitted because of the introduction of societal need (i.e. demand) to normalize environmental impacts, thus also introducing a natural link between social and environmental sustainability.

The laundry case study indicated that contemporary washing machine water use can be considered sustainable (in the UK market), but less efficient products are close to the acceptable limit. The sustainable volume of water that may be used to provide a laundry service was determined with an allocation of planetary boundaries that was generous toward unpaid household services. Compared to a strictly economic allocation, this approach permits a greater environmental impact within the defined sustainable limits. Conversely, processes that are not consumer-facing will need to have lower impacts for Earth-systems to operate within planetary boundaries. There is yet to be unanimous agreement on a fair allocation system, and this is recognized as the greatest source of variance between assessments (further analysis in Fig. S7),[5] but an emphasis on what people do, rather than how much they pay for it, is commensurate with an equitable society.

The sustainable amount of water use, land use, and fertilizer use in agriculture was also justified using the nutritional content of the food produced. It was found that the mean average environmental impact of food production is unsustainable in several instances, particularly for animal products. However, when considering the range of environmental impacts incurred by different farming practices in different locations, there are many examples of sustainable agricultural practices. Service-weighted Product Level Absolute

Sustainability was used to imply a sustainable limit to the environmental impacts associated with several foodstuffs, and in doing so introduced targets for future practices.

In defining food demand categories (energy, protein, portions of fruit and vegetables) it is assumed the consumption of fruit and vegetables per capita is diverse enough to deliver sufficient micronutrients, and protein intake provides sufficient quantities of essential amino acids. Service-weighted Product Level Absolute Sustainability could be calculated to consider individual vitamins and minerals with a more complex economic allocation. An additional allocation accounting for fiber was considered, but ultimately discounted because whole plant-based foods contain large quantities of fiber, meaning a very high allocation of planetary boundaries was attributed to the provision of fiber and very little to the other macronutrients. Therefore, it has also been assumed that diets can be adopted to provide sufficient fiber (30 g per capita per day) by virtue of consuming whole foods (grains, vegetables, etc.).

Service-weighted Product Level Absolute Sustainability can identify the excessive use of fertilizers relative to nutritional benefit,[29] and provide product-level objectives for agriculture.[30] This exercise reiterates well understood consequences of farmed meat and the need for sustainable diets,[31] but also identifies areas and practices that support sustainable food production. Where environmental impacts are identified as unsustainably high, Service-weighted Product Level Absolute Sustainability calculations indicate the required reduction to (for example) freshwater use, or perhaps whether different crops could be grown sustainably in their place. The responsibility of consumers is also recognised in the Service-weighted Product Level Absolute Sustainability framework. To take one example, the land use associated with producing potatoes has a Service-weighted Product Level Absolute Sustainability of 104% based on the demand created by a future flexitarian diet (Fig. 4B).

Slightly reducing food waste from 17.75% to 13.25% of our basic nutritional requirement would make land use associated with potato production sustainable in this scenario.

Some general limitations to the methodology have also been inferred through these case studies. The emphasis on the service provided by finished products means Service-weighted Product Level Absolute Sustainability does not evaluate the individual components in a product or the stages of a manufacturing processes to identify sustainability hotspots. However, the benefit of improved product performance can be evaluated, thus sacrificing the producer-orientated assessment of other absolute sustainability methodologies and replacing it with an end-user focus. Regardless, manufacturers can still use the Service-weighted Product Level Absolute Sustainability concept to introduce overall performance and sustainability targets for their products, and then determine which raw materials or manufacturing processes need to be reviewed for an acceptable environmental impact.

There are knowledge gaps that prevent Service-weighted Product Level Absolute Sustainability being applied to some environmental impacts. Unquantified planetary boundaries, e.g. chemical pollution, cannot be used to calculate Service-weighted Product Level Absolute Sustainability at present. The freshwater use planetary boundary has recently been reinterpreted as several smaller planetary boundaries relating to different sources of water,[32] but because they are yet to be quantified they too cannot be used. Where the appropriate data is available, Service-weighted Product Level Absolute Sustainability is an appropriate tool to inform policy regarding the sale of inefficient products that could be regarded as unsustainable, or to create absolute sustainability certification schemes.

Experimental procedures

Resource availability

All the source data used in this article is available from the cited references. The reinterpretation of this data is documented in the article and the Supplemental Information. Washing machine case study data was sourced from DEFRA,[22] In The Wash,[18] ONS,[23] Samsung,[19] Springmann et al.,[7] and Whirlpool.[20] Food production case study data was sourced from FAO,[25,33] Gerten et al.,[28] Poore and Nemecek,[26] Springmann et al.,[7] and USDA.[24]

Methods

The allocation of the freshwater planetary boundary (PB^{water}, km^3/year) to UK laundry demand was determined with Equation 1 according to the population affected (P) and GVA (also see Fig. 2A). The absolute sustainability of laundry freshwater use was then able to be calculated with Equation 2 for a given washing machine model (results in Fig. 2B). Data is provided in Fig. S1 and Table S1-3.

Eq. (1)
$$PB^{water}_{UK\ laundry} = \left(PB^{water}_{global} - PB^{water}_{agriculture}\right) \cdot \frac{P_{UK}}{P_{global}} \cdot \frac{GVA^{laundry}_{UK}}{\left(GVA^{total}_{UK} - GVA^{agriculture}_{UK}\right)}$$

Eq. (2)
$$SPLASH^{water}_{laundry} = \frac{impact\ (freshwater\ use, m^3)}{PB^{laundry}_{UK}\ (m^3/year)} \Bigg/ \frac{service\ (wash\ cycles)}{demand_{UK}\ (wash\ cycles/year)}$$

Equation 3 shows the calculation of nutritional units (NU, /kg) for the example of tomatoes and calories (data in Table S5). Equation 4 represents the gross production value (V, $) attributable to energy provision of global tomato production. 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 economic value of agricultural crops not intended as food (e.g. cotton, tobacco) and herbs and spices were not converted into NU.

Eq. (3) $$NU_{tomatoes}^{energy}(per\ kg) = \frac{energy\ (kcal/kg)}{energy\ demand\ per\ capita\ per\ day\ (kcal)}$$

Eq. (4) $$V_{tomatoes}^{energy}\ (\$) = V_{tomatoes}(\$) \cdot \frac{NU_{tomatoes}^{energy}\ (per\ kg)}{NU_{tomatoes}^{energy}(per\ kg)+NU_{tomatoes}^{protein}(per\ kg)+NU_{tomatoes}^{fruit/veg}(per\ kg)}$$

Equation 5 is required to obtain the sum of the global production value of food attributable exclusively to energy provision in the form of calories (Fig. 3B). This value was used to assign a proportion of a planetary boundary to the provision of food calories according to Equation 6 (Fig. 3C, also see Table S6 and S7).

Eq. (5) $$V_{global}^{energy}(\$) = \sum_{k=food\ group}^{n=all\ foods} V_k^{energy}\ (\$)$$

Eq. (6) $$PB_{energy}^{water} = PB_{agriculture}^{water} \cdot \frac{V_{global}^{energy}(\$)}{V_{global}(\$)}$$

The sub-division of environmental impact (Impact$_{\text{tomatoes}}$) into individual contributions for each macronutrient is given in Equation 7 for the example of water use for tomato production (Fig. 3F).

Eq. (7) $$Impact_{tomatoes}^{energy}(water\ use,\ m^3/kg) = \frac{Impact_{tomatoes}\ (water\ use, m^3/kg) \cdot NU_{tomatoes}^{energy}(per\ kg) \cdot V_{global}^{energy}(\$)}{NU_{tomatoes}^{energy} \cdot V_{global}^{energy} + NU_{tomatos}^{protein} \cdot V_{global}^{protein} + NU_{tomatoes}^{fruit/veg} \cdot V_{global}^{fruit/veg}}$$

The Service-weighted Product Level Absolute Sustainability calculation describing water use for tomato production is calculated using Equation 8 (calorie basis) with results shown in Fig. 3G.

Eq. (8) $$SPLASH_{tomatoes}^{water} = \frac{Impact_{tomatoes}^{energy}\ (m^3/kg)}{PB_{energy}^{water}(m^3/year)} \Bigg/ \frac{service\ (kcal/kg)}{demand\ (kcal/year)}$$

Supplemental information

Supplemental information containing data tables for all the Figures and discussion herein and expanded data analysis is provided. Additional supplemental data (as a spreadsheet) containing the contemporary and predicted future environmental impacts (land use, water use, fertilizer use) of a variety of foods expressed as Service-weighted Product Level

Absolute Sustainability, and the methodology for calculating the economic allocation of environmental impact and planetary boundaries by macronutrient is provided.

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