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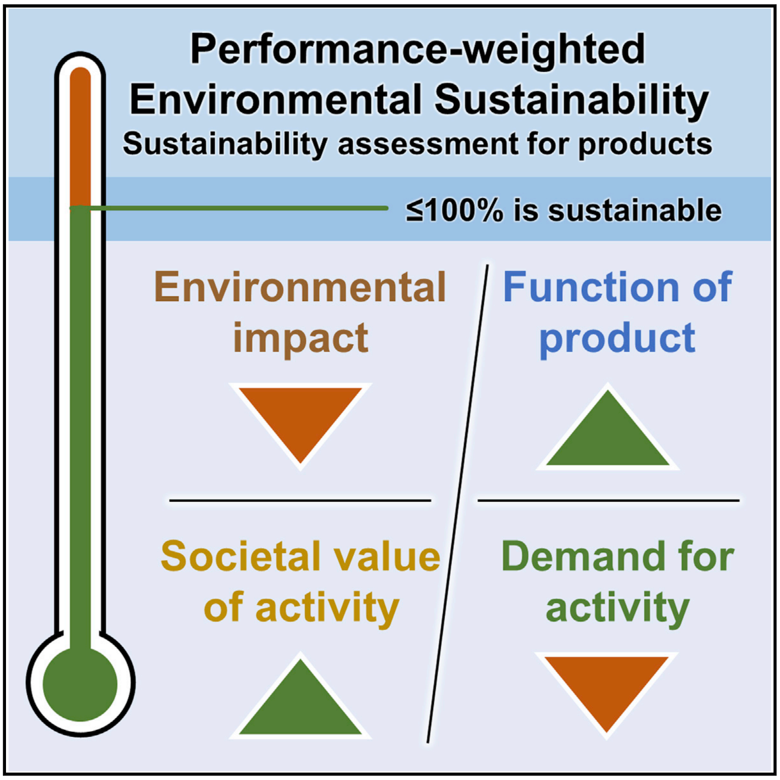
One Earth

Calculating the sustainability of products based on their efficiency and function

Graphical abstract



Highlights

- A quantitative environmental sustainability metric for products is proposed
- The function and efficiency of a product are used to normalize environmental impacts
- Washing machines using $\leq$ 33 L of water in the UK are considered sustainable

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In brief

Sustainability assessments inform policy makers, businesses, and citizens of actions that mitigate the irreversible deterioration of the environment. However, quantifying the sustainability of a product is not straightforward since it needs to consider the environmental impacts in the context of the safe operating limits of the Earth system with respect to regional or local context. Here, I propose a new metric to assess definitive sustainability by calculating the maximum permissible environmental impact of a product in terms that are comparable between products with different functions and across impact categories.

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Calculating the sustainability of products based on their efficiency and function

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SCIENCE FOR SOCIETY When a product is described as sustainable, it is often used qualitatively to suggest it has a lower environmental impact than other products. However, these assessments lack regional or local context. Using washing machines and water use as an example, common sustainability assessments would not consider the regional availability of water or competing water demands such as for essential food growth. Considering these aspects is important if we are to determine how much of a specific activity or product/service use is permissible without compromising local, regional, or even global safe operating limits. An assessment approach that considers the efficiency and purpose of a product/service is therefore needed. Based on the approach presented in this paper, in the UK, a typical washing machine is sustainable with respect to water use given water availability, but its carbon emissions are unsustainable given the country's net positive carbon footprint. This research can be used to communicate the environmental sustainability of products in a definitive way, avoiding subjective or misleading claims, and to enable comparisons between products.

SUMMARY

The planetary boundaries concept has identified limits that must be preserved to ensure a safe operating space for humanity. We are threatening, and in some cases have exceeded, these limits in part through unsustainable use of products and services. Life cycle assessments of individual products, while valuable in evaluating the environmental footprint of a product, lack inherent impact targets. Here, I propose performance-weighted environmental sustainability as a numerical indicator to determine if the environmental impacts of a product are sustainable. Using the example of a washing machine, its function (laundry) was used to normalize the environmental impact of its freshwater use. The results suggest that a UK washing machine using 33 L of water per wash cycle is sustainable. This metric makes it possible to determine acceptable environmental impacts for individual products based on what they are used for and to inspire sustainable product design.

INTRODUCTION

The deterioration of the environment undermines efforts to sustain essential activities 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 (see Figure S1).[2] National or global scale multi-criteria indicators such as these may introduce emission targets to normalize an impact category,[3] but they do not typically provide a well-defined 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.[4,5] A planetary boundary (PB) defines the tipping point of an Earth system process, beyond which the ecosystem becomes unstable with potentially disastrous consequences. The best-known PB is the safe limit to atmospheric CO_2 concentration with respect to climate change. Other examples relevant to this work are provided in Table 1. Where appropriate, the contribution of natural processes is subtracted from a PB to give the "safe operating space" for humanity.[6] The scale and ambition of the PB concept suits international policies,[7] but they can also be divided into allocations to suggest a maximum environmental impact for different activities.[8–10] This "downscaling" exercise has been performed for agriculture by

Table 1. The magnitude of planetary boundaries; uncertainty ranges are shown in brackets

Planetary Boundary	Global scale[a]	Safe operating space[b]	Agricultural allocation[c]
Freshwater use (km^3/year)	4,000 (4,000–6,000)	4,000	1,980 (780–3,190)
Land use change (million km^2)	18.2 (18.2–24.2)	18.2	12.6 (10.6–14.6)
N fixation (Tg/year)	62 (62-82)	62	Not applicable
N fertilizer application (Tg/year)	Undefined	Undefined	69 (52-113)
P fertilizer application (Tg/year)	6.2 (6.2–11.2)	6.2	16 (8-17)
Ocean acidification (mol)	2.75 (2.41–2.75)	0.69	Undetermined
Atmospheric aerosol loading	0.25 (0.25–0.50)	0.11	Undetermined
Climate change (energy imbalance, W/m^2)	1.0 (1.0–1.5)	1.0	Undetermined
Climate change (CO_2 concentration)	350 (350–450) ppm	72 ppm	4,700 (4,300–5,300) Tg CO_2-eq./year
Stratospheric ozone depletion (DU)	275 (261–275)	15	Undetermined

Tg is terragrams (10^{12} g). N is nitrogen and P is phosphorus.

[a] From Rockström et al.[4] and Steffen et al.[5]

[b] From Ryberg et al.[6]

[c] From Springmann et al.[11]

Springmann et al. (Table 1)[11] and for various other examples.[12–15] For example, phosphorus emissions to water from the Indian dairy industry are 667 million kg/year, exceeding their allocated share of the safe operating space by 1,300%.[16]

Contemporary environmental sustainability assessments can now provide a reasonably definitive interpretation of regional activities, but product-level sustainability assessments have not been derived from the same theoretical basis. The state-of-the-art in product-level environmental metrics have incorporated an efficiency scale to justify resource use,[17] but there is no unambiguous target that would signify the product is sustainable. Conventional life cycle assessment (LCA) approaches are applicable to individual products but also lack inherent impact targets. 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.[18] This means comparisons between dissimilar products with different functions remain invalid because environmental impacts are specific to a functional unit (e.g., the grams of CO_2 emitted by a vehicle per kilometer).

Here I present a solution to the problem of downscaling a safe operating space for a product-level sustainability assessment, also resolving some limitations of LCA mid-point indicators (e.g., overlooking the final services/functions provided by a product). The transition from a regional-scale sustainability assessment to a product-level metric was performed on the basis of product efficiency. Normalizing product performance by demand for its function then eliminates specific functional units for different products, enabling comparisons between products with different functions. When the actual environmental impact is below the allocated safe operating space, the product is considered sustainable with respect to that impact category. This work has used washing machines as a case study. The assessment differs from a previously published European-wide evaluation of laundry practices because individual washing machines have been differentiated by their efficiency (i.e., if more clothes are washed for the same environmental impact, that washing machine is more sustainable).[6] This study provides a robust means of determining the environmental sustainability of products without the limitations of functional units. The procedure is limited to environmental impacts with a corresponding PB, and so LCA remains important to cover a greater breadth of environmental impacts. The results are intended to be used by manufacturers to develop design targets but can also be used to communicate sustainable practice to consumers given that demand for products is a crucial variable in the assessment.

RESULTS

Method summary

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, so the function of a product can be represented as a variable in sustainability assessments instead of economic value, for example.[19] Combining environmental impacts with the societal benefit obtained from the function of a product reveals how the choices made in the design of products define their sustainability. Specifically, the ratio between the quantified function of a product and demand for that function, compared with the ratio between its environmental impact and the maximum permissible impact of activities that cumulatively represent the demand category, can be used to indicate if a product is sustainable (further information is given in Notes S1–S5 and Figures S2–S4). The resulting metric is called performance-weighted environmental sustainability (Figure 1) and abbreviated to PwES where necessary. It is a unitless indicator and can be calculated for any environmental impact category with a corresponding PB. Any value over 100% is regarded as unsustainable.

The sustainability of industries can theoretically be scaled down further to represent individual products (i.e., by dividing environmental impacts by the number of products), but this is uninformative without differentiating between inefficient and efficient products. The PwES metric deems the function of a product equally as important as its environmental impact in determining its sustainability. Here, function is defined as the benefit received from the intended purpose of a product (see Note S1). Increased performance or an extended product lifespan improves the function of a product. Function is normalized by demand for that function, a consequence of consumer behavior. Demand must be a measurable and quantitative entity with a defined duration, typically 1 year (Note S2). The ratio between function and demand differentiates between efficient and inefficient products, and it is only a direct scaling factor of environmental impact if all products contributing to demand provide an identical function over the same time span. In reality, the product-level resolution of the PwES metric makes it clearer to product designers and users whether greater efficiency can justify a higher environmental impact during production or use (see Note S5). Various future scenarios can be analyzed with PwES to predict necessary improvements in technology (manifested as function) or determine a sustainable level of consumption (the demand) for a given population.

A proportion of the planetary boundaries must be allocated to the demand category relevant to the product in question. Appropriate methods are debated,[16,20] but the basis of relative economic value is typically applied. The PwES metric differs in this respect, firstly because a significant proportion of the relevant planetary boundaries may first be reserved for agriculture (as determined by Springmann et al.[11]; see Figure 1). Then the remaining available safe operating space is shared between activities based on their value to society, with over 40% dedicated to childcare, volunteering, housekeeping, and other services that are not represented in traditional economic allocations. PwES is demonstrated herein for freshwater use of performing laundry with a washing machine. This case study was chosen because an equivalent regional assessment had been previously published,[6] and therefore the results can be compared. The format of the PwES metric is shown in Equation 1 for this case study.

Environmental sustainability of home laundry

The PwES of using a washing machine is demonstrated firstly with respect to freshwater use using data from 2016 for the UK. The calculation and results are summarized in Figure 2 and Note S6, Tables S1–S7, and Figure S5. An error analysis is explained in Note S7 (Tables S8 and S9). Interactive data are provided in https://doi.org/10.5281/zenodo.7240305, tab "S1." The function of a washing machine was defined 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 (this does not change the result; see Table S10). The freshwater use environmental impact included in the PwES calculations is blue water (surface water and groundwater) to match the PB definition. The water use of washing machines was sourced from manufacturer specifications.[21–23] The fresh water required to generate electricity and manufacture detergents is also included (https://doi.org/10.5281/zenodo.7240305, tab "S1"). The total freshwater use is 43.5 L, of which 33 L is used directly in the wash cycle (Figure 2A, red box). The only other major source of freshwater consumption is due to leaks in the water supply (8.6 L, based on London, UK, see methods). An alternative, high water use washing machine is also included for comparison, consuming 72 L per wash cycle. The water consumed to manufacture the washing machine was divided by the expected number of uses to arrive at the water use impact per wash cycle. It was assumed a 6-kg-load household washing machine is used 260.1 times a year with a lifespan of 12 years, as obtained from a previous LCA.[24] The annual demand for UK wash cycles was calculated by multiplying the number of UK households by the clothes washing frequency stated above. Function and demand can alternatively be defined in terms of the mass of clean clothes obtained, evaluating the effect of how full the washing machine is rather than using the average value (Table S11).

The allocation of freshwater use for domestic laundry requires the global PB to be scaled down to represent the UK (therefore matching the scope of the demand variable). A per capita allocation is made, assigning 0.89% of the PB to the UK. Gross value added (GVA) was then used to assign portions of the PB to different activities. This can be problematic for activities that generate little or no monetary value. To rectify this, PwES emphasizes the importance of a product's function over its monetary/value, and commensurately the value of unpaid household services in the UK have been valued and a GVA assigned for the year 2016.[25] This was used to finalize the allocation of the freshwater use PB for this assessment. Laundry accounts for almost 3% of this expanded UK GVA measure (see Table S6). The other relevant sectors (electricity generation, water supply, and detergent manufacture for laundry) were added to arrive at 3.13%. Wash cycles performed in a launderette require a separate assessment deriving their own PB allocation (safe operating space). Equation 2 provides the full equation for this per capita method (annotated as P in relevant figures), which calculates 1,114 billion liters per year is available for performing household laundry in the UK (Figure 2A, gold box).

$$PwES^{water}_{laundry} = \frac{impact(freshwater\ use, m^3)}{PB^{water}_{UK\ laundry}(m^3/year)} \Bigg/ \frac{function(wash\ cycles)}{demand_{UK}(wash\ cycles/year)} \qquad \text{(Equation 1)}$$

$$PB^{water}_{UK\ laundry} = PB^{water}_{global} \cdot \frac{P_{UK}}{P_{global}} \cdot \frac{GVA^{laundry}_{UK}}{GVA^{total}_{UK}} \qquad \text{(Equation 2)}$$

The quantities of water required by agriculture are much higher than would be permitted by Equation 2, and so not to impair food production, a large allocation of freshwater use can be put aside for agricultural purposes.[11] The contribution of laundry to UK (expanded) GVA after excluding food production is 3.15% (of the non-agricultural economy), meaning 564 billion liters of

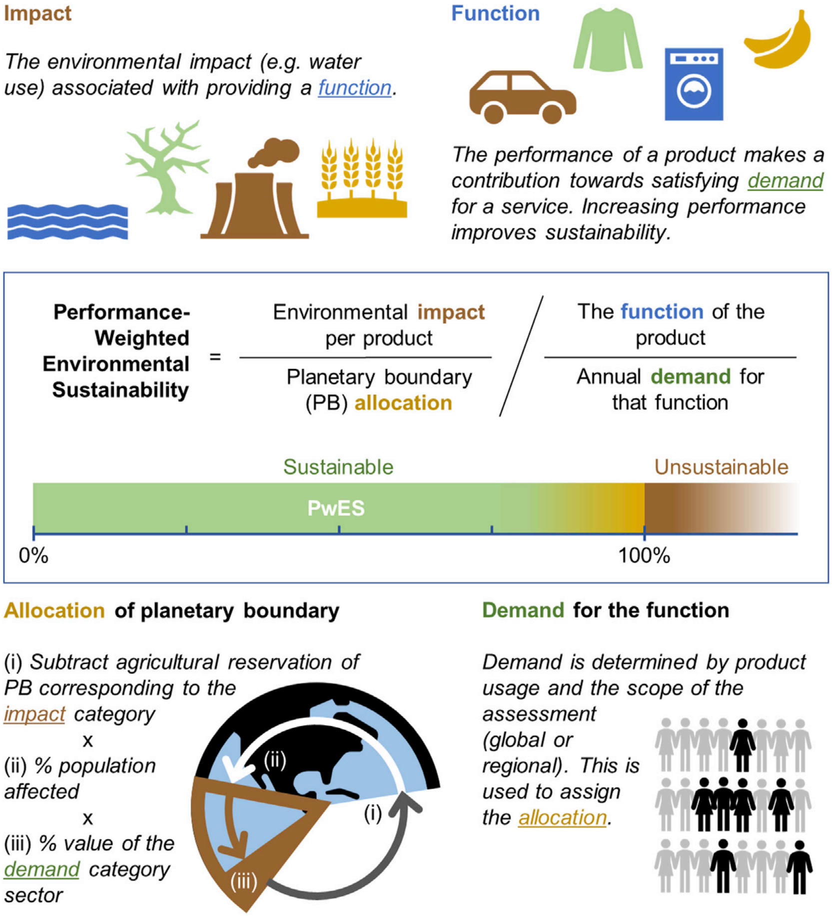

Figure 1. A new sustainability assessment format using product performance to interpret environmental impact

The performance-weighted environmental sustainability calculation is inset within the border, including an indicative scale of potential values (values > 100% are considered unsustainable). The four variables of the metric are briefly explained in the corners of the figure. This generic example is for non-agricultural products. See Note S1–S5 for more information.

freshwater would be available as the sustainable limit to satisfy annual UK demand for clothes washing by this measure. This approach is denoted as the P/A allocation method, according to Equation 3 and applied in Figure 2A.

$$PB^{water}_{UK\ laundry} = \left(PB^{water}_{global} - PB^{water}_{agriculture}\right)\cdot\frac{P_{UK}}{P_{global}}\cdot\frac{GV\,A^{laundry}_{UK}}{\left(GV\,A^{total}_{UK} - GV\,A^{agriculture}_{UK}\right)} \qquad \text{(Equation 3)}$$

The PwES of domestic laundry with a washing machine consuming 33 L of water per wash cycle was calculated as 54%, rising to 116% for more water-intensive washing machines (Figure 2B, P/A allocation method as shown in Equation 3). The latter is unsustainable (i.e., >100%) based on UK demand in the year 2016. If the agricultural reservation is removed (P method, as in Equation 2), PwES values are approximately halved. The data for Figure 2 are given in https://doi.org/10.5281/zenodo.7240305, tab "S3."

The water consumed by hand washing clothes (within the home) is typically greater than a washing machine per garment (Note S8 and Table S12, https://doi.org/10.5281/zenodo.7240305, tab "S4"), but a washing machine is expected to be less sustainable than hand washing clothes in other impact categories, particularly GHG emissions (Figure 3 and Table S13, P method of Equation 2). Impact data were sourced from the work of Ryberg et al.[6] and converted to impact per wash cycle. The climate change PB allocations are exceeded by more than 400%, and the impact on nitrogen flows and ocean acidification is also unsustainable. Surprisingly, freshwater use is among the most sustainable impacts of performing laundry, although the agricultural reservation was not applied in Figure 3 to keep consistency with the other impact categories without defined agriculture-specific planetary boundaries. The stratospheric ozone depletion PwES of laundry using a washing machine was the lowest at 0.05%, which is not shown on Figure 3 for scale reasons (https://doi.org/10.5281/zenodo.7240305, tab "S5").

Regional differences in sustainability

The function-to-demand ratio in the PwES metric offers greater specificity than a general LCA functional unit (of one wash cycle for example) when comparing regions. Where a product is operated is very important when defining demand, but it also affects the impact incurred and the allocation of planetary boundaries. Figure 4 (also see tab "S6" in https://doi.org/10.5281/zenodo.7240305, and Tables S14–S17) shows that the freshwater PwES value of UK home laundry of 54% (P/A method, Equation 3) is higher than using an equivalent washing machine in Türkiye (48%) or Australia (38%). Domestic laundry has a freshwater use PwES of 84% when the washing machine is operated in Japan. The total freshwater use impact of a washing machine is increased by water leaks. This adds 9 L per wash cycle in the UK (based on London) but 20 L in Türkiye (national average, see Figure 4A). Australia (2 L of leaked water per wash cycle, based on Sydney) and Japan (0.7 L, based on Tokyo) have a more efficient water supply infrastructure. Furthermore, the water used to produce electricity is notably higher in Türkiye compared with the other aforementioned regions due to the high proportion of hydropower in the energy mix. This is exacerbated by the higher average energy use of washing machines in Türkiye,[26] adding 30 L of water per wash cycle. In the other three territories, the freshwater use associated with electricity generation is only 0.5–1.5 L per wash cycle.

The allocation of the freshwater use PB was performed using the P/A method (Equation 3). This is a per capita scaling

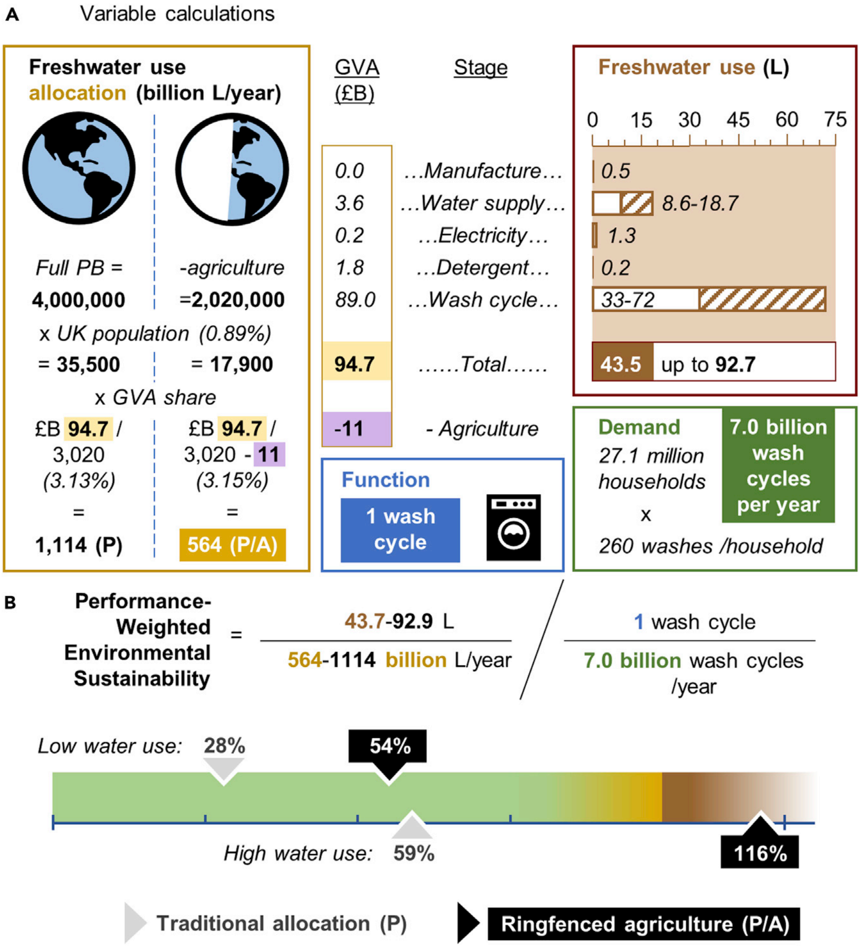

Figure 2. The calculation of freshwater use performance-weighted environmental sustainability of UK washing machines

(A) Metric variables and allocations of the freshwater planetary boundary to match the scope of demand (P and P/A allocation methods of Equation 2 and Equation 3 respectively). The allocation defines the maximum impact of the activity (annual UK laundry) that can be considered sustainable with respect to freshwater use. Two freshwater use scenarios are used, a low-water-use and a high-water-use washing machine.

(B) Performance-weighted environmental sustainability (PwES) of two washing machines with different water efficiencies. Data are also calculated in Tables S1–S7.

method, so the largest allocation is awarded to Japan because it has the largest population of the countries studied (Figure 4B). Japan also has the greatest demand for wash cycles in terms of annual washes per household (approximately double other regions)[26] and the number of households (Figure 4C). High demand means performing laundry is least sustainable in Japan, despite having the lowest water use (Figure 4D).

Weighting by ability to pay and water scarcity

Sustainability assessments are often subjected to correction factors and weighted variables to assist with comparisons. PwES uses regionalized principles to derive demand and PB allocations but can be modified to consider the ability of a region to operate sustainably. Two principles are applied here, firstly introducing an economic weighting to the PB allocation (an ‘‘ability to pay’’ weighting) and alternatively converting freshwater use into water scarcity footprint with the use of available water remaining (AWARE) characterization factors (CFs). The latter accounts for local availability of water (tab ‘‘S7’’ in https://doi.org/10.5281/zenodo.7240305).

Figure 5A demonstrates how to apply an ability to pay principle. Previously proposed by Hjalsted et al.,[16] the GDP of a country was used to modify the P/A PB allocation method into the economy-weighted E/A method in Equation 4. A constant of 0.243 is required so the PB allocation is redistributed correctly. This constant makes it clear that a country with the mean average GDP per capita will have approximately one-quarter of the PB allocation that would be ordinarily derived from Equation 3. The graph in Figure 5A shows the trend line of how the economic weighting is less than 1 for the majority of countries, including the four regions assessed in this work. For instance, the freshwater use PB allocation for the UK operation of washing machines is 564 billion liters per year (P/A method, Equation 3), and scaled by a factor of 0.06 derived from GDP to give a revised allocation of 34 billion liters per year (E/A method, Equation 4). The resulting PwES values indicate laundry using a washing machine is unsustainable in all the countries that were assessed (Figure 5B and Tables S18–21).

$$PB^{water}_{UK\ laundry} = \left(PB^{water}_{global} - PB^{water}_{agriculture}\right)\cdot\frac{P_{UK}}{P_{global}}\cdot\left(\frac{GDP^{per\ capita}_{global}}{GDP^{per\ capita}_{UK}}\cdot 0.243\right)\cdot\frac{GVA^{laundry}_{UK}}{\left(GVA^{total}_{UK} - GVA^{agriculture}_{UK}\right)}$$

(Equation 4)

Alternatively, regional water scarcity can be introduced to the PwES calculation (denoted as cf._PwES) in order to consider water availability (Equation 5 for UK laundry). The freshwater use of a product can be multiplied by the AWARE CF corresponding to the region (and time period if appropriate) to produce the water scarcity footprint of the product (Figure 5C).[27] For example, the 33 L of water directly used in the wash cycle is multiplied by a CF of 1.25 to reflect the water scarcity in the UK. Other sources of freshwater use were also multiplied by the corresponding CF. Using water scarcity footprint in the cf._PwES calculation dramatically decreases the calculated sustainability of laundry in the water-scarce regions of Australia and Türkiye (Figure 5D and Tables S22–S25). In Japan, it is reduced to 54%.

$$cf\_PwES^{water}_{laundry} = \frac{\sum cf_{UK} \cdot imapact(freshwater\ use, m^3 - eq.)}{PB^{water}_{UK\ laundry}(m^3/year)} \Bigg/ \frac{function(wash\ cycles)}{demand_{UK}(wash\ cycles/year)} \quad \text{(Equation 5)}$$

Annual fluctuations in water availability and demand

The final example of PwES (and cf._PwES) examines the sustainability of freshwater use for laundry using a washing machine in London, UK, across the year. Variable monthly water scarcity and demand for wash cycles means activities can become unsustainable at certain times in the year. For some products, this can inform how and when we use them. The PwES variables are provided in Figure 6A. The annual freshwater use PB allocation was adjusted to the new spatial and temporal resolution (tab "S8" in https://doi.org/10.5281/zenodo.7240305). Freshwater use remains sustainable throughout the year accounting for monthly fluctuations in demand, with a range of PwES values between 45% and 67% (Figures 6B and 6C).[28] Accounting for water scarcity, the freshwater use of laundry is determined as unsustainable from July to September. However, the average monthly cf._PwES is 78%. This is slightly higher than for the UK as a whole due to the higher AWARE CF for London but still sustainable.

DISCUSSION

This study has suggested that the water use of laundry using a washing machine consuming 33 L per wash cycle is generally sustainable. The assessment included water use impacts from water supply, energy supply, manufacturing, and the detergent. The impact of producing detergent and manufacturing the washing machine had a minimal influence on sustainability because almost all the consumptive water use is associated with operating the washing machine. The impact of an inefficient supply of water (due to leaks) is significant in some regions (UK and Türkiye). To increase water sustainability, reducing the wash cycle water volume is a priority. This also reduces the losses in the water supply associated with using the washing machine.

The most unsustainable aspect of a washing machine is the GHG emissions associated with energy use. Manufacturers already recognize that efficiency is vital for sustainable laundry, with 30°C wash cycles being promoted, and detergents designed for low-temperature washes. The quantitative results of PwES help to provide an objective target and suggest GHG emissions per wash cycle typically need to be less than a quarter of what they presently are (Figure 3). This is unrealistic, so the cooperation of consumers is also needed. To reduce water use and GHG emissions, consumers can act to ensure their washing machine is full and to wash clothes less frequently where possible. This is very apparent with the function-to-demand ratio included in the PwES metric. An under-capacity wash cycle of 3 kg of clothes compared with 6 kg will double the PwES, and this would be considered unsustainable in the UK (P/A allocation method of Equation 3, see Table S26).

The PwES values that were obtained are an order of magnitude lower than other carrying capacity-based sustainability assessments, as compared in Figure S6 with the calculation summarized in Table S27.[6] This discrepancy is largely due to the introduction of unpaid services, valued in GVA-equivalent units, into the PB allocation. The use of final consumption expenditure was also considered as a means of downscaling planetary boundaries, but the resulting safe operating space for laundry is very small and is very sensitive to the price of products (tab "S1" in https://doi.org/10.5281/zenodo.7240305 and Table S28). This approach was rejected because sustainability becomes less dependent on environmental impact or function, with expensive articles appearing to be more sustainable than cheaper products because the PB allocation increases with expenditure. Conversely, the GVA of unpaid services is proportional to how much an activity is performed. The preferred freshwater use

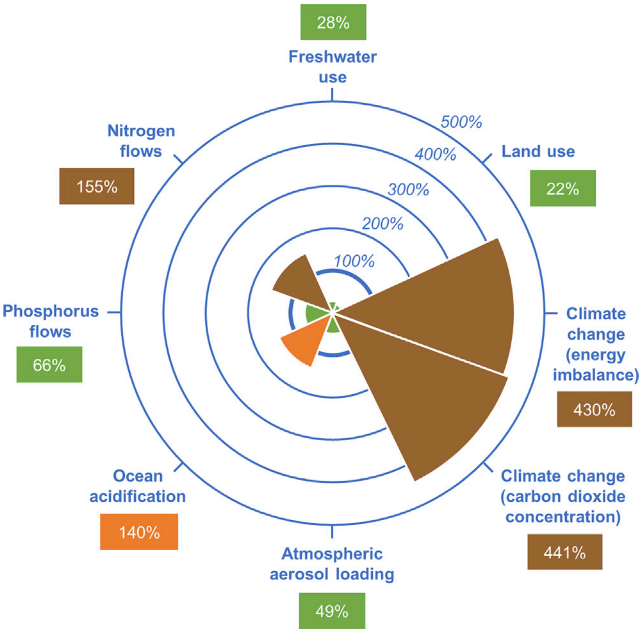

Figure 3. Performance-weighted environmental sustainability results for a washing machine in different impact categories

Equal per capita planetary boundary allocation (P method, Equation 2) has been used. The same methodology has been followed as explained in Figure 2, extended to other environmental impacts with corresponding planetary boundaries. Green entries are considered sustainable. Orange entries would be sustainable at the upper limit of the safe operating space error range. Brown entries are considered unsustainable. Data are calculated in Table S13.

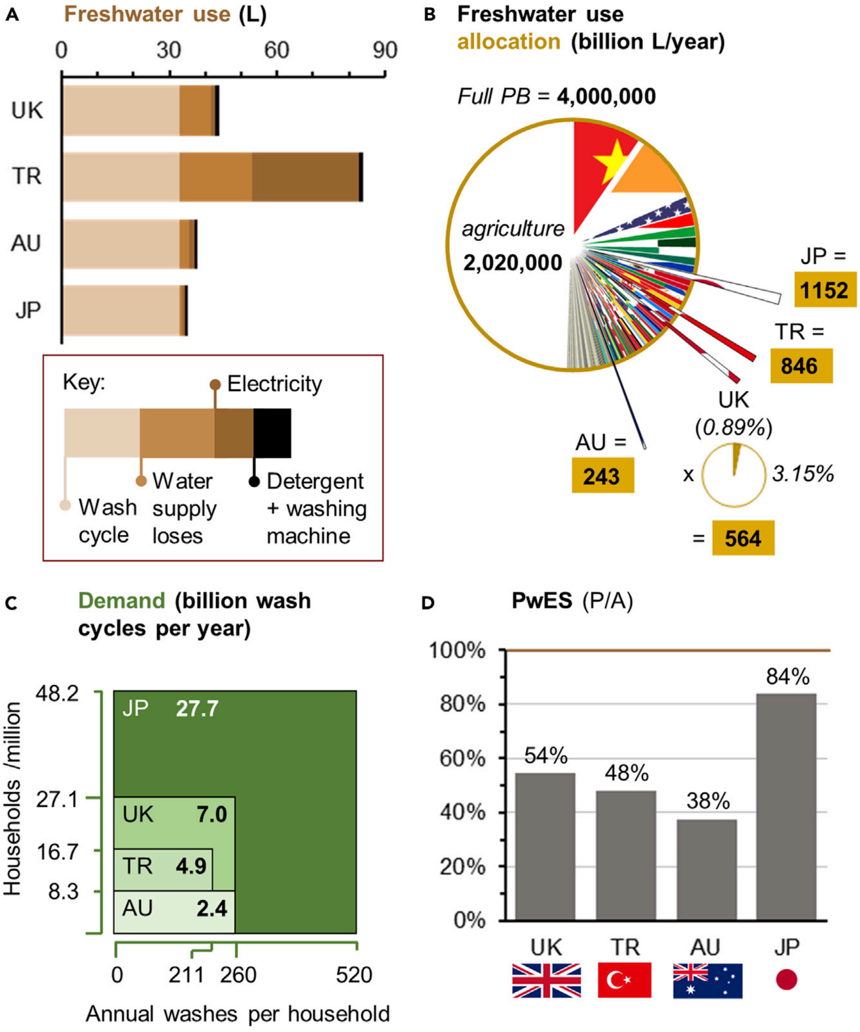

Figure 4. Freshwater use performance-weighted environmental sustainability of washing machines in different countries

(A) Freshwater use impact by category and country of a typical washing machine.

(B) Per capita allocation of the freshwater use planetary boundary. As illustrated for the UK, the final planetary boundary allocation is obtained by multiplying with the economic allocation to household laundry (the same as in Figure 2).

(C) Calculating demand for wash cycles by multiplying the number of households by annual washes per household. The product is represented visually by the size of the rectangles.

(D) PwES values (P/A allocation method, Equation 3). Data are calculated in Tables S14–S17. All freshwater use impacts are considered sustainable (>100%).

PwES calculation based on Equation 3 is more proportionate with the overall evaluation of Steffen et al.,[5] who calculate that freshwater use globally is about two-thirds of the sustainable limit. The large agricultural allocation of planetary boundaries in the P/A allocation method, Equation 3, ensures PwES calculations are balanced for both agricultural and non-agricultural activities. The sustainability of high value sectors (e.g., financial services, real estate) is not judged against GVA alone as it is in the conventional allocation method (P, as in Equation 2).

Figure 4 illustrates the importance of demand as a variable in sustainability assessments by comparing regions. It is most interesting that demand per capita for wash cycles varies more between regions than the environmental impact, so demand is responsible for more variance of PwES values than freshwater use impact (Figure 4). Some nations could encourage a reduction in washing machine use to lower demand and reduce PwES values. Demand also changes with time, with PwES increasing from 54% in 2016 (typical value of UK laundry using a domestic washing machine, Figure 2) to 57% by 2019 (Table S29).

An economic weighting was also applied to the PB allocation to distinguish between the “ability to pay” of different regions. This modification was found to have an extreme effect, significantly reducing the safe operating space assigned for laundry in each of the regions featured in this study (Figure 5A). Ultimately the results (Figure 5B) would make it impossible to operate a washing machine sustainability in most regions. In the UK, just 5 L of water per wash cycle would be considered unsustainable (Table S30). This specific economic weighting cannot be recommended because how sustainability is perceived becomes determined mostly by the wealth of the region, and less by the value of a product’s function or its environmental impact. In some instances, the concept of an economic weighting is acceptable, for example, to justify government investment in impact mitigation (public infrastructure or transportation for instance). More research is needed into economic weightings that produce attainable sustainability targets.

An allowance for water availability was also investigated (Figure 5C), and the high water use and low water availability in Türkiye is reflected in the cf._PwES value of 1,016% that was obtained (Figure 5D). Conversely, operating a washing machine in Japan is determined as more sustainable because of high water availability. Modifying freshwater use PwES for water scarcity is a valid approach given that the environmental impact of freshwater use is localized, whereas GHG emissions generally have a global-level impact (on climate change). Nevertheless, activities in regions experiencing low water availability will be perceived as less sustainable than the same activities practiced in regions with plentiful freshwater. It is advisable that both PwES and cf._PwES values are obtained to judge what measures are appropriate and realistic to achieve.

The monthly temporal resolution of the London case study (Figure 6) confirms that seasonal variations in demand and water scarcity are important. Consumers can try to reduce their washing machine use in times of water scarcity, but the fundamental need for laundry throughout the year means there is

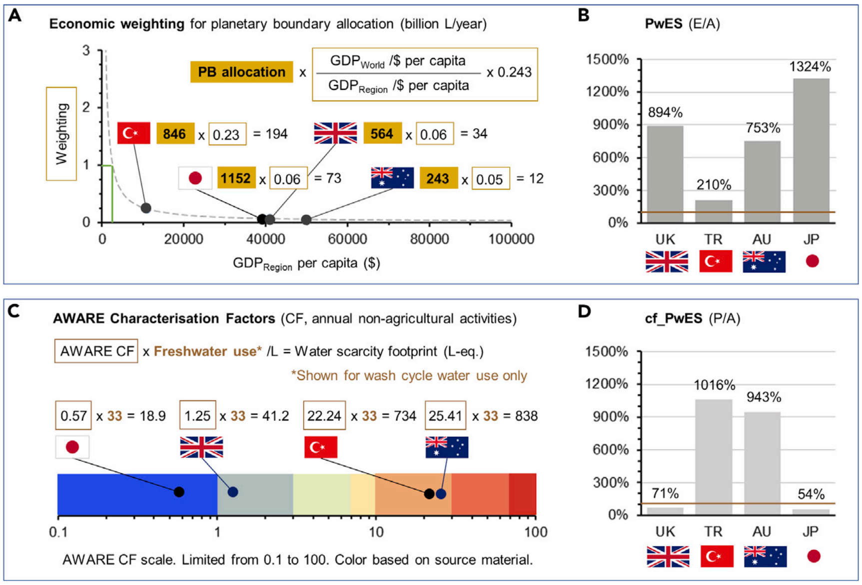

Figure 5. Alternative sustainability assessments modified with an ability to pay principle or local water availability

(A) The correlation between GDP and the economic weighting added to the planetary boundary allocation (inset equation), annotated with four examples. Gold color filled boxes are conventional P/A allocations. Gold border boxes are the economic weighting factor.

(B) PwES values (E/A allocation method, Equation 4, Tables S18–S21).

(C) The modification of freshwater use (bold values) into water scarcity footprint using characterization factors (CFs, values in brown boxes). Freshwater use (e.g., 33 L) is multiplied by the CF to account for water availability.

(D) Modified cf._PwES values (P/A allocation method, Equation 3, see Tables S22–S25).

also an emphasis on product designers and water suppliers to reduce water use per wash cycle, as guided by PwES values.

There are some limitations to the application of the PwES metric. The emphasis on the function of finished products means PwES does not evaluate the individual components in a product or the stages of a manufacturing processes to identify sustainability hotspots. However, the overall benefit of improved product performance and lower environmental impacts can be evaluated, sacrificing the producer-orientated assessment of some sustainability methodologies,[29] and replacing it with an end-user focus. Unquantified planetary boundaries, e.g., chemical pollution, or the sources of water contributing to the overall freshwater use PB,[30] cannot be used to calculate PwES at present.

In summary, PwES offers a new perspective on the sustainable use and function of products. It represents a shift from reducing environmental impact to maximizing the function of a product for the impact incurred. The function-to-demand ratio within the PwES metric captures the differences between products without the barrier of different functional units. Societal need (i.e., demand) differentiates between regions and introduces a natural link between social and environmental sustainability.

This metric has the potential to contextualize research findings at the regional or global scale into terms more relatable to individuals, revealing how consumers or service providers can operate products sustainably. PwES can inform policy regarding the sale of inefficient products, clarify claims of sustainability, and offer a relatable perspective that will help science communication and standards.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

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Materials availability

This study did not generate new unique materials.

Data and code availability

All the source data used in this article are available from, or derived from, the cited references. The reinterpretation of this data is documented in the article and the supplemental information. The data required for Figures 2–6 are available at https://doi.org/10.5281/zenodo.7240305.

Methods

The planetary boundaries were obtained from the literature.[4,5] The agricultural PB reservations were obtained from Springmann et al.[11] Per capita allocations of the planetary boundaries to a region were made on the basis of population.[31] Economic allocations were based on GVA,[32] expanded to include the hypothetical value of unpaid services in the UK.[25] For other regions without expanded GVA data, the relative GVA equivalents of laundry and other unpaid services from the UK were added to basic GVA (on a percentage basis). The value of water supply[32–35] was multiplied by the proportion of water supplied to households[36] and then multiplied by the proportion of water used by households to operate washing machines.[37] The value of electricity supply was obtained from national accounts.[32,33] This value was revised down to match the proportion of electricity used to operate washing machines by households.[6,38] The GVA generated by detergents was taken from Ryberg et al.[6] There was no washing machine manufacturing industry in the UK in 2016, so no economic value was ascribed to it.[39] This was applied to other regions for consistency.

The water use of washing machines was sourced from manufacturer specifications.[21–23] Leaks in the water supply were sourced from national records, multiplying the leak rate by the end point water use.[40–43] The water intensity of electricity generation was derived from the national energy mix[44–47] and water intensity by energy source.[48] The water use per kWh of energy generated was multiplied by the energy use of a washing machine per wash cycle to contribute to the environmental impact used in PwES calculations.[26] The freshwater use to produce detergent for one wash cycle was obtained from Ryberg et al.[6] The freshwater use to manufacture a washing machine[49] was divided by the expected number of wash cycles during the product's lifespan, and this too was added to the total freshwater use environmental impact.[24]

Demand for domestic laundry was calculated from the annual wash cycles performed per household[24,26] multiplied by the households in the region.[26,50]

To use the ability to pay principal for the E/A allocation method (Equation 4), GDP per capita data was obtained from the World Bank.[51] This principle essentially assumes that the higher the GDP per capita of a country is, the more capable that country is to reduce its environmental impacts. The formula in Equation 4 was then applied as described by Hjalsted et al.[16]

The water scarcity footprint was calculated by applying a dimensionless CF to freshwater use as shown in Equation 5. AWARE factors for non-irrigation

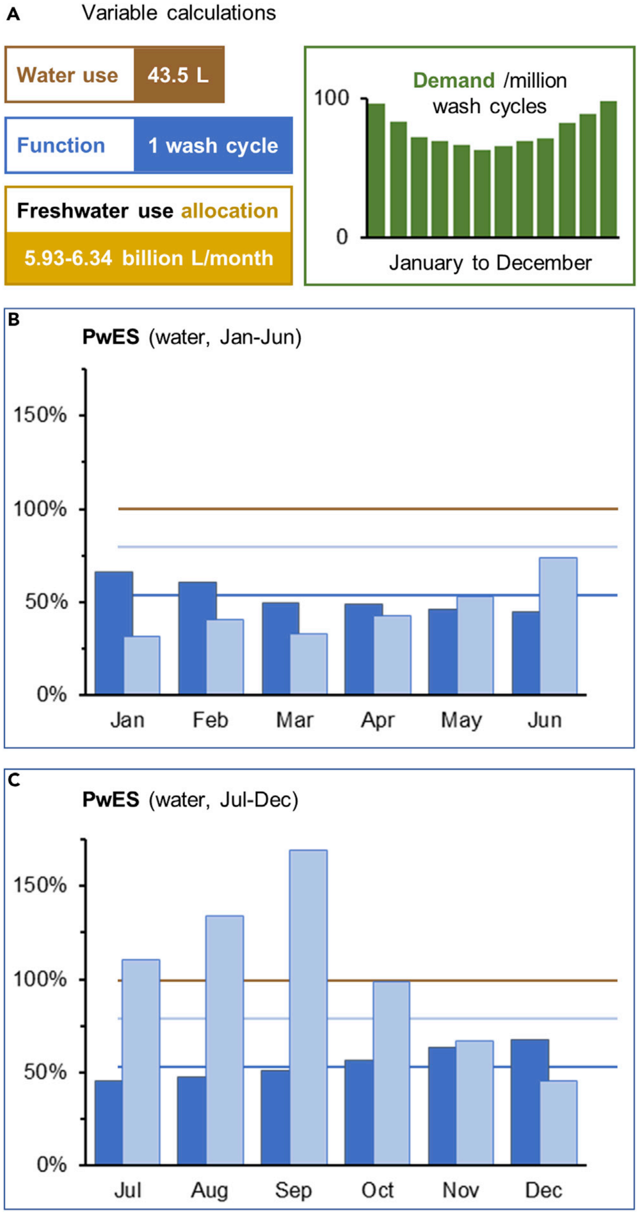

Figure 6. London washing machine performance-weighted environmental sustainability by month

(A) Performance-weighted environmental sustainability variables. The monthly freshwater use planetary boundary allocation varies by virtue of the number of days in the month. Otherwise, the principle is the same as illustrated in Figure 2.

(B) The PwES for months January–June (2016).

(C) The PwES for months July–December (2016). Dark bars are PwES values derived from freshwater use. Light bars are PwES values based on water scarcity footprint. Brown line is sustainable limit (100%). Blue lines are annual average PwES values. See tab "S8" in https://doi.org/10.5281/zenodo.7240305.

purposes were used as CFs.[27] The annual AWARE factor describing non-irrigation water use in the UK is 1.248.[27] The appropriate CF for each source of freshwater use was applied, so in the case of freshwater use for washing machine and detergent manufacturing, the CF used does not necessarily correspond to the region in which the washing machine is operated (as listed in tab "S1" in https://doi.org/10.5281/zenodo.7240305). If a process could not be located, e.g., the synthesis of surfactants for the detergent formulation, the generic global CF of 20.3 was used.

Freshwater use PwES assessments based on monthly demand require that the demand category and PB allocation are reduced to the same timescale. Monthly AWARE factors are available.[27] Weekly household washing machine use was acquired for the UK,[28] and converted into monthly quantities. Population[52] and household[53] data for London were used for the case study represented in Figure 6.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.10.011.

AUTHOR CONTRIBUTIONS

J.S. analyzed the data and wrote the manuscript.

DECLARATION OF INTERESTS

The author declares no competing interests.

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REFERENCES

1. Wendling, Z.A., Emerson, J.W., de Sherbinin, A., and Esty, D.C. (2020). 2020 Environmental Performance Index (Yale Center for Environmental Law & Policy). https://epi.yale.edu.
2. Witulski, N., and Dias, J.G. (2020). The sustainable society index: its reliability and validity. Ecol. Indic. *114*, 106190. https://doi.org/10.1016/j.ecolind.2020.106190.
3. Castellani, V., Benini, L., Sala, S., and Pant, R. (2016). A distance-to-target weighting method for Europe 2020. Int. J. Life Cycle Assess. *21*, 1159–1169. https://doi.org/10.1007/s11367-016-1079-8.
4. Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., III, Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., et al. (2009). A safe operating space for humanity. Nature *461*, 472–475. https://doi.org/10.1038/461472a.
5. Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., et al. (2015). Planetary boundaries: guiding human development on a changing planet. Science *347*, 1259855. https://doi.org/10.1126/science.1259855.
6. Ryberg, M.W., Owsianiak, M., Clavreul, J., Mueller, C., Sim, S., King, H., and Hauschild, M.Z. (2018). How to bring absolute sustainability into decision-making: an industry case study using a planetary boundary-based methodology. Sci. Total Environ. *634*, 1406–1416. https://doi.org/10.1016/j.scitotenv.2018.04.075.
7. Pickering, J., and Persson, Å. (2020). Democratising planetary boundaries: experts, social values and deliberative risk evaluation in Earth system governance. J. Environ. Policy Plan. *22*, 59–71. https://doi.org/10.1080/1523908X.2019.1661233.
8. Clift, R., Sim, S., King, H., Chenoweth, J., Christie, I., Clavreul, J., Mueller, C., Posthuma, L., Boulay, A.-M., Chaplin-Kramer, R., et al. (2017). The challenges of applying planetary boundaries as a basis for strategic decision-making in companies with global supply chains. Sustainability *9*, 279. https://doi.org/10.3390/su9020279.
9. Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., Hauschild, M.Z., Kerkhof, A., King, H., Margni, M., et al. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. Environ. Res. Lett. *15*, 083001. https://doi.org/10.1088/1748-9326/ab89d7.

10. Ryberg, M.W., Andersen, M.M., Owsianiak, M., and Hauschild, M.Z. (2020). Downscaling the planetary boundaries in absolute environmental sustainability assessments - a review. J. Clean. Prod. *276*, 123287. https://doi.org/10.1016/j.jclepro.2020.123287.

11. Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., et al. (2018). Options for keeping the food system within environmental limits. Nature *562*, 519–525. https://doi.org/10.1038/s41586-018-0594-0.

12. Ryberg, M.W., Bjerre, T.K., Nielsen, P.H., and Hauschild, M. (2021). Absolute environmental sustainability assessment of a Danish utility company relative to the planetary boundaries. J. Ind. Ecol. *25*, 765–777. https://doi.org/10.1111/jiec.13075.

13. Algunaibet, I.M., Pozo, C., Galán-Martín, Á., Huijbregts, M.A.J., Mac Dowell, N., and Guillén-Gosálbez, G. (2019). Powering sustainable development within planetary boundaries. Energy Environ. Sci. *12*, 1890–1900. https://doi.org/10.1039/C8EE03423K.

14. Bjørn, A., Sim, S., Boulay, A.-M., King, H., Clavreul, J., Lam, W.Y., Barbarossa, V., Bulle, C., and Margni, M. (2020). A planetary boundary-based method for freshwater use in life cycle assessment: development and application to a tomato production case study. Ecol. Indic. *110*, 105865. https://doi.org/10.1016/j.ecolind.2019.105865.

15. Chandrakumar, C., McLaren, S.J., Jayamaha, N.P., Ramilan, T., and Ramilan, T. (2019). Absolute sustainability-based life cycle assessment (ASLCA): a benchmarking approach to operate agri-food systems within the 2°C global carbon budget. J. Ind. Ecol. *23*, 906–917. https://doi.org/10.1111/jiec.12830.

16. Hjalsted, A.W., Laurent, A., Andersen, M.M., Olsen, K.H., Ryberg, M., and Hauschild, M. (2021). Sharing the safe operating space: exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels. J. Ind. Ecol. *25*, 6–19. https://doi.org/10.1111/jiec.13050.

17. Franklin-Johnson, E., Figge, F., and Canning, L. (2016). Resource duration as a managerial indicator for Circular Economy performance. J. Clean. Prod. *133*, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023.

18. Bach, V., Lehmann, A., Görmer, M., and Finkbeiner, M. (2018). Product environmental footprint (PEF) pilot phase–comparability over flexibility? Sustainability *10*, 2898. https://doi.org/10.3390/su10082898.

19. Clift, R., and Wright, L. (2000). Relationships between environmental impacts and added value along the supply chain. Technol. Forecast. Soc. Change *65*, 281–295. https://doi.org/10.1016/S0040-1625(99)00055-4.

20. Lucas, P.L., Wilting, H.C., Hof, A.F., and van Vuuren, D.P. (2020). Allocating planetary boundaries to large economies: distributional consequences of alternative perspectives on distributive fairness. Glob. Environ. Change *60*, 102017. https://doi.org/10.1016/j.gloenvcha.2019.102017.

21. In The Wash (2018). How much water does a washing machine use (In the Wash)?. https://inthewash.co.uk/washing-machines/how-much-water-does-a-washing-machine-use.

22. Samsung (2020). Product Help and Support (Samsung). https://www.samsung.com/uk/support/home-appliances/how-much-water-does-my-samsung-washing-machine-use-per-cycle.

23. Whirlpool (2020). Laundry Articles (Whirlpool). https://www.whirlpool.com/blog/washers-and-dryers/he-washing-machine-water-usage.html.

24. Department for Environment Food and Rural Affairs (2010). Longer Product Lifetimes - EV0445 (DEFRA). http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=17047.

25. Office for National Statistics (2018). Household Satellite Account, UK:2015 and 2016 (ONS). https://www.ons.gov.uk/economy/nationalaccounts/satelliteaccounts/articles/householdsatelliteaccounts/2015and2016estimates.

26. Pakula, C., and Stamminger, R. (2010). Electricity and water consumption for laundry washing by washing machine worldwide. Energy Efficiency *3*, 365–382. https://doi.org/10.1007/s12053-009-9072-8.

27. Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., et al. (2018). The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int. J. Life Cycle Assess. *23*, 368–378. https://doi.org/10.1007/s11367-017-1333-8.

28. Department of Energy & Climate Change (2013). Household Electricity Survey. A Study of Domestic Product Use (DECC). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/208097/10043_R66141HouseholdElectricitySurveyFinalReportissue4.pdf.

29. Bjørn, A., Sim, S., King, H., Patouillard, L., Margni, M., Hauschild, M.Z., and Ryberg, M. (2020). Life cycle assessment applying planetary and regional boundaries to the process level: a model case study. Int. J. Life Cycle Assess. *25*, 2241–2254. https://doi.org/10.1007/s11367-020-01823-8.

30. Gleeson, T., Wang-Erlandsson, L., Zipper, S.C., Porkka, M., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S.E., Piemontese, L., Gordon, L.J., et al. (2020). The water planetary boundary: interrogation and revision. One Earth *2*, 223–234. https://doi.org/10.1016/j.oneear.2020.02.009.

31. United Nations (2019). World population prospects (UN) population. https://population.un.org/wpp/.

32. United Nations (2017). National Accounts Statistics: Main Aggregates and Detailed Tables, 2016 (UN). https://unstats.un.org/unsd/nationalaccount/pubsDB.asp?pType=3.

33. Office for National Statistics (2022). Gross Value Added (GVA) (ONS). https://www.ons.gov.uk/economy/grossvalueaddedgva.

34. Statista (2020). Gross Value Added (GVA) by the Water Supply and Waste Services Industry in Australia in Financial Years 2010 to 2020 (Statista). https://www.statista.com/statistics/1029610/australia-gva-added-water-supply-and-waste-services-industries/.

35. Japanese Government Statistics (2022). E-stat (Japanese Government Statistics). https://www.e-stat.go.jp/en.

36. Thames Water (2020). Final Water Resources Management Plan 2019 (Thames Water). https://www.thameswater.co.uk/media-library/home/about-us/regulation/water-resources/technical-report/current-and-future-demand-for-water.pdf.

37. McGinley (2015). How to Make a Glass of Water (McGinley). https://www.mcginley.co.uk/news/how-to-make-a-glass-of-water/bp142/.

38. UK Parliament (2017). Electricity and Renewables Sector Report (UK Parliament). https://www.parliament.uk/globalassets/documents/commons-committees/Exiting-the-European-Union/17-19/Sectoral-Analyses/12-Electricity-and-Renewables-Report.pdf.

39. British Broadcasting Corporation (2016). Ebac Returns Washing Machine Manufacture to UK (BBC). https://www.bbc.co.uk/news/uk-england-tees-37485194.

40. Thames Water (2017). Annual Report and Financial Statements 2016/17 (Thames Water). https://www.thameswater.co.uk/media-library/home/about-us/investors/our-results/previous-reports/2016-17/annual-report-2016-17.pdf.

41. Earth Island Institute (2021). In Water-Stressed Turkey, Cities Look to Solutions New and Old (Earth Island Institute). https://www.earthisland.org/journal/index.php/articles/entry/drought-water-stressed-turkey-solutions/.

42. Sydney Water (2017). Annual Report 2016-17 (Sydney Water). https://www.sydneywater.com.au/content/dam/sydneywater/documents/annual-report-2016-17.pdf.

43. Outokumpu (2022). The Secret to Tokyo's Low Water Leakage Rate (Outokumpu). https://www.outokumpu.com/en/expertise/2021/the-secret-to-tokyos-low-water-leakage-rate.

44. UK Government (2022). Energy Trends: UK Electricity Data on Electricity Generation, Supply, Consumption and Fuel Use for Generation (GOV UK). https://www.gov.uk/government/statistics/electricity-section-5-energy-trends.

45. U.S. Energy Information Administration (2020). Turkey (EIA). https://www.iea.org/countries/turkey.

46. U.S. Energy Information Administration (2020). Australia (EIA). https://www.eia.gov/international/analysis/country/aus.

47. U.S. Energy Information Administration (2020). Japan (EIA). https://www.eia.gov/international/analysis/country/jpn.

48. Jin, Y., Behrens, P., Tukker, A., and Scherer, L. (2019). Water use of electricity technologies: a global meta-analysis. Renew. Sustain. Energy Rev. *115*, 109391. https://doi.org/10.1016/j.rser.2019.109391.

49. Bole, R. (2006). Life-Cycle Optimization of Residential Clothes Washer Replacement (University of Michigan). https://css.snre.umich.edu/sites/default/files/css_doc/CSS06-03.pdf.

50. Office for National Statistics (2016). Families and Households in the UK: 2016 (ONS). https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2016.

51. World Bank (2022). GDP Per Capita (Current US$) (World Bank). https://data.worldbank.org/indicator/NY.GDP.PCAP.CD.

52. Office for National Statistics (2016). Regional Gross Value Added (Balanced), UK: 1998 to 2016 (ONS). https://www.ons.gov.uk/economy/grossvalueaddedgva/bulletins/regionalgrossvalueaddedbalanceduk/1998to2016.

53. Greater London Authority (2016). Economic Evidence Base for London 2016 (Greater London Authority). https://www.london.gov.uk/sites/default/files/chapter8-economic-evidence-base-2016.pdf.