Calculating the sustainability of products based on their efficiency and function

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 ≤ 33 L of water in the UK are considered sustainable

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In brief

Sustainability assessments inform policymakers, 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.

Article

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Calculating the sustainability of products based on their efficiency and function

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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 CO2 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

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.
Springmann et al. (Table 1) and for various other examples. 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%. 

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, 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. 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 CO₂ 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). 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. 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

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

| Planetary Boundary                        | Global scale | Safe operating space | Agricultural allocation |
|------------------------------------------|--------------|----------------------|-------------------------|
| Freshwater use (km³/year)                | 4,000 (4,000–6,000) | 4,000 | 1,980 (780–3,190) |
| Land use change (million km²)            | 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/m²) | 1.0 (1.0–1.5) | 1.0 | Undetermined |
| Climate change (CO₂ concentration)      | 350 (350–450) ppm | 72 ppm | 4,700 (4,300–5,300) Tg CO₂-eq./year |
| Stratospheric ozone depletion (DU)      | 275 (261–275) | 15 | Undetermined |

Tg is teragrams (10¹² g). N is nitrogen and P is phosphorus.

*From Rockström et al.* and Steffen et al.*

*From Ryberg et al.*

*From Springmann et al.*
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, 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.: 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, and therefore the results can be compared. The format of the PwES metric is shown in Equation 1 for this case study.

\[
P_{\text{PwES}_{\text{water laundry}}} = \frac{\text{impact (freshwater use, m}}{m^3/\text{year}}} {\text{function (wash cycles)}} \times \frac{\text{demand}_{\text{UK}} (\text{wash cycles/ year})}{PB_{\text{water UK laundry}} (m^3/\text{year})} \tag{Equation 1}
\]

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. 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. 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. 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).

\[
P_{\text{water UK laundry}} = \frac{PB_{\text{water global}}}{P_{\text{global}}} \times \frac{GVA_{\text{laundry UK}}}{GVA_{\text{UK}}} \tag{Equation 2}
\]

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. 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
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.

\[
PB_{\text{water}}^{\text{UK laundry}} = \frac{PB_{\text{water}}^{\text{global}} - PB_{\text{water}}^{\text{agriculture}}}{P_{\text{UK}} / P_{\text{global}}} \cdot \left( \frac{GV_{A_{\text{laundry}}}}{GV_{A_{\text{total}}^{\text{UK}}} - GV_{A_{\text{agriculture}}}} \right)
\]  

(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. 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, 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, 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...
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) 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., the GDP of a country was used to modify the P/A PB allocation method by a factor of 0.06 derived from GDP to give a revised allocation of 34 billion liters per year (P/A method, Equation 3), and scaled 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).

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). 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%.

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).

\[
\text{cf}_{\text{PwES}}_{\text{water}} = \frac{\sum \text{cf}_{\text{UK}} \cdot \text{impact(freshwater use, m}^3 \text{– eq.)}}{\text{P} \text{water}_{\text{UK, laundry}} (m}^3 \text{/year})} \div \frac{\text{function(wash cycles)}}{\text{demand}_{\text{UK}} (\text{wash cycles/year})}
\]

(Equation 5)

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](https://doi.org/10.5281/zenodo.7240305)
PwES calculation based on Equation 3 is more proportionate with the overall evaluation of Steffen et al., 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 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 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
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, 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 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**

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**Materials availability**
This study did not generate new unique materials.

**Methods**

The planetary boundaries were obtained from the literature. The agricultural PB reservations were obtained from Springmann et al. Per capita allocations of the planetary boundaries to a region were made on the basis of population. Economic allocations were based on GVA, expanded to include the hypothetical value of unpaid services in the UK. For other regions without expanded GDA 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 was modified with an ability to pay principle. The GVA generated by detergents was taken from Ryberg et al. The freshwater use to manufacture a washing machine was obtained from national records, multiplying the leak rate by the end point water use. The water intensity of electricity generation was derived from the national energy mix and water pollution, or the sources of water contributing to the overall freshwater use PB 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.

**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.
purposes were used as CFs. The annual AWARE factor describing non-irrigation water use in the UK is 1.248. 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. Weekly household washing machine use was acquired for the UK, and converted into monthly quantities. Population and household 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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Supplemental information

Calculating the sustainability of products based on their efficiency and function

James Sherwood
**Figure S1. Categorization of sustainability assessments using representative examples.** Relevant to Fig. 1. Entries: P Bs, planetary boundaries;\(^1\) safe and just space framework;\(^2\) share of safe operating space (SOS);\(^3\) PwES, performance-weighted Environmental Sustainability; environmental performance (EP) index;\(^4\) eco(logical) footprint;\(^5\) EDP, environmentally adjusted net domestic product;\(^6\) human development (HD) index;\(^7\) SISD, synthetic indicator of sustainable development;\(^8\) sustainable society (SS) index;\(^9\) PEF, product environmental footprint (an example of environmental life cycle assessment);\(^10\) LCCA, life cycle cost analysis;\(^11\) social life cycle assessment (LCA).\(^{12}\)
Figure S2. An example of equivalence between product-level and regional sustainability. Relevant to Fig. 1. Left: frequency of products (blue bars) and environmental impact (red data point) where efficiency does not vary. Right: Corresponding PwES values (black bars) compared to regional assessment (red line). This is an illustrative concept not a case study.
Figure S3. A demonstration of how function and environmental impact can influence sustainability with constant environmental impact between products. Relevant to Fig. 1. Left: frequency of products (blue bars) and environmental impact (red data point) with varying levels of function efficiency. Right: Corresponding PwES values (black bars) compared to regional assessment (red line). This is an illustrative concept not a case study.
Figure S4. A demonstration of how function and environmental impact can influence sustainability with variable environmental impacts between products. Relevant to Fig. 1. Left: frequency of products (blue bars) and environmental impact (red data point) with varying levels of function efficiency. Right: Corresponding PwES values (black bars) compared to regional assessment (red line). This is an illustrative concept not a case study.
Figure S5. The boundary of the laundry sustainability assessment. Relevant to Fig. 2. Boundaries define the scope of freshwater use impact and the planetary boundary allocation in the PwES calculation. Literature allocations refer to the work of Ryberg et al. (2018) (3).
Figure S6. Comparison between product-level and regional sustainability assessments. Relevant to Fig. 2. A) Performance-weighted Environmental Sustainability (PwES) describing water use of an efficient UK washing machine. B) EU regional assessment of laundry habits (left fraction), downscaled and rearranged into the format of PwES (right fraction) and annotated with the magnitude difference between equivalent values.
Supplemental Tables

Table S1. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient UK washing machine. Relevant to Fig. 2. Not ringfencing agriculture (P method, Eq. (S2)).

| Variable                  | Value   | Scope        |
|---------------------------|---------|--------------|
| Impact /m³                | 0.0435  | Efficient    |
| Function /wash cycles     | 1       |              |
| PB allocation /m³-year⁻¹  | 1.11x10⁹| See Table S7.|
| Demand /wash cycles-year⁻¹| 7.05x10⁹| UK (13).     |
| PwES                      | 28%     |              |

Table S2. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an inefficient UK washing machine. Relevant to Fig. 2. Not ringfencing agriculture (P method, Eq. (S2)).

| Variable                  | Value   | Scope        |
|---------------------------|---------|--------------|
| Impact /m³                | 0.0927  | Inefficient  |
| Function /wash cycles     | 1       |              |
| PB allocation /m³-year⁻¹  | 1.11x10⁹| See Table S7.|
| Demand /wash cycles-year⁻¹| 7.05x10⁹| UK (13).     |
| PwES                      | 59%     |              |

Table S3. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient UK washing machine. Relevant to Fig. 2. Ringfencing agriculture (P/A method, Eq. (S1), single wash version).

| Variable                  | Value   | Scope        |
|---------------------------|---------|--------------|
| Impact /m³                | 0.0435  | Efficient    |
| Function /wash cycles     | 1       |              |
| PB allocation /m³-year⁻¹  | 5.64x10⁸| See Table S7.|
| Demand /wash cycles-year⁻¹| 7.05x10⁹| UK (13).     |
| PwES                      | 54%     |              |

Table S4. Performance-weighted Environmental Sustainability (PwES) of an inefficient UK washing machine. Relevant to Fig. 2. Ringfencing agriculture (P/A method, Eq. (S1)).

| Variable                  | Value   | Scope        |
|---------------------------|---------|--------------|
| Impact /m³                | 0.0927  | Inefficient  |
| Function /wash cycles     | 1       |              |
| PB allocation /m³-year⁻¹  | 5.64x10⁸| See Table S7.|
| Demand /wash cycles-year⁻¹| 7.05x10⁹| UK (13).     |
| PwES                      | 116%    |              |
Table S5. UK laundry demand. Relevant to Fig. 2 to Fig. 5.

| Year | UK population (14) | UK households /million (15.) | Demand /million wash cycles |
|------|--------------------|-------------------------------|----------------------------|
| 2016 | 66,297,994         | 27.1                          | 7,049                      |
| 2019 | 67,530,161         | 27.8                          | 7,231                      |

Table S6. UK expanded GVA. Relevant to Fig. 1 and Fig. 2. Selected data for 2016 (16,17).

| Sector                   | Absolute value /£billion | Relative value (including agriculture) | Relative value (excluding agriculture) |
|--------------------------|--------------------------|----------------------------------------|----------------------------------------|
| Household services       |                          |                                        |                                        |
| Transport                | 358                      | 11.9%                                  | 11.9%                                  |
| Childcare                | 352                      | 11.7%                                  | 11.7%                                  |
| Housing                  | 199                      | 6.6%                                   | 6.6%                                   |
| Nutrition                | 158                      | 5.2%                                   | 5.3%                                   |
| Laundry                  | 89                       | 2.9%                                   | 3.0%                                   |
| Adult care               | 59                       | 2.0%                                   | 2.0%                                   |
| Volunteering             | 24                       | 0.8%                                   | 0.8%                                   |
| Clothing                 | 3                        | 0.1%                                   | 0.1%                                   |
| Business sectors         |                          |                                        |                                        |
| Water supply             | 23                       | 0.8%                                   | 0.8%                                   |
| Electricity supply       | 26                       | 0.9%                                   | 0.9%                                   |
| Detergent manufacturing  | 2                        | 0.1%                                   | 0.1%                                   |
| Washing machine manufacturing | 0                  | 0%                                     | 0%                                     |
| Agriculture              | 11                       | 0.4%                                   | n/a                                    |
| Other                    | 1716                     | 57%                                    | 57%                                    |
| Total                    | 3020                     | 100%                                   |                                        |

Table S7. Freshwater planetary boundary (PB) UK laundry allocation. Relevant to Fig. 2.

| Planetary Boundary /m³-year⁻¹ | Scope                          | Population share | Economic value | Allocation /m³-year⁻¹ |
|-------------------------------|--------------------------------|------------------|----------------|-----------------------|
| 4.00x10¹²                     | Full PB assigned by Rockström et al. (18). | 0.89%            | 3.13%          | 1.11x10⁸              |
| 2.02x10¹²                     | Minus agriculture (19).         | 0.89%            | 3.15%          | 5.64x10⁸              |
Table S8. Uncertainty of variables in the washing machine case study (efficient washing machine, P/A allocation method). Published error ranges have been converted into 95% confidence probability distributions.

| Variable                        | Mean       | Distribution     | Standard deviation | Literature error range                  |
|---------------------------------|------------|------------------|--------------------|-----------------------------------------|
| Function /wash cycles           | 1          | n/a              | 0.2                |                                         |
| Demand /annual wash cycles      | 7.05x10^8  | Lognormal        | 0.11               | -6.0% to +9.2% (20).                    |
| Impact /L                       | 43.5       | Lognormal        | 0.11               |                                         |
| Freshwater use PB /L per year   | 4.00x10^{15} | None/ exponential | n/a                | 4.00 x10^{15} to 6.00 x10^{15} (1).     |
| Agricultural water use /L per year | 1.98x10^{15} | Normal          | 4.46x10^{14}       | 7.80x10^{14} to 3.19 x10^{15} (19).    |
| GVA (case study) /£             | 9.47x10^{10} | Lognormal      | 0.11               | -6.0% to +9.2% (16).                    |
| GVA (agriculture) /£            | 1.10x10^{10} | Normal          | 1.65x10^{8}        | -2.6% to +2.6% (21).                    |
| GVA (UK total) /£               | 3.02x10^{12} | Normal          | 4.53x10^{10}       | -2.6% to +2.6% (17).                    |
| UK population                   | 6.63x10^{7}  | Normal          | 1.33x10^{5}        | -0.2% to +0.2% (14).                    |
| Global population               | 7.46x10^{8}  | Normal          | 1.12x10^{8}        | -2.0% to +2.0% (22).                    |

Table S9. Sensitivity coefficients of variables effecting the PwES value of a washing machine.
Variables were perturbed by 10%. Standard PwES value of this product is 54%.

| Variable                        | Sensitivity coefficient | Perturbed PwES value (%change) |
|---------------------------------|-------------------------|--------------------------------|
| Function                        | 0.91                    | 49% (-5%)                       |
| Demand                          | 1.00                    | 60% (+5%)                       |
| Impact                          | 1.00                    | 60% (+5%)                       |
| Freshwater use PB               | 1.65                    | 45% (-9%)                       |
| Agricultural water use          | 1.09                    | 60% (+6%)                       |
| GVA (case study scope)          | 0.91                    | 49% (-5%)                       |
| GVA (agriculture)               | 0.004                   | 54% (0%)                        |
| GVA (UK total)                  | 1.00                    | 60% (+5%)                       |
| UK population                   | 0.91                    | 49% (-5%)                       |
| Global population               | 1.00                    | 60% (+5%)                       |
Table S10. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient UK washing machine (full lifespan basis). Relevant to Fig. 2. Ringfencing agriculture (P/A method, Eq. (S1)).

| Variable               | Value   | Scope         |
|------------------------|---------|---------------|
| Impact /m³             | 137     | Efficient     |
| Function /wash cycles  | 3145    | UK (13)       |
| PB allocation /m³-year⁻¹ | 5.64x10⁸ | See Table S7. |
| Demand /wash cycles-year⁻¹ | 7.05x10⁹ | UK (13).     |
| PwES                   | 54%     |               |

Table S11. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient UK washing machine (clothes mass basis, 1 wash cycle). Relevant to Fig. 2. Ringfencing agriculture (P/A method, Eq. (S1)).

| Variable               | Value   | Scope         |
|------------------------|---------|---------------|
| Impact /m³             | 0.0435  | Efficient     |
| Function /kg clean clothes | 6       | UK (13).     |
| PB allocation /m³-year⁻¹ | 5.64x10⁸ | See Table S7. |
| Demand /kg clean clothes-year⁻¹ | 4.23x10¹⁰ | UK (13).   |
| PwES                   | 54%     |               |

Table S12. Performance-weighted Environmental Sustainability (PwES) of handwashing 1 jumper in a small basin with respect to freshwater use. Ringfencing agriculture (P/A allocation method). Function and demand based on mass of clean clothes acquired.

| Variable               | Value  | Scope         |
|------------------------|--------|---------------|
| Impact /m³             | 0.007  |               |
| Function /kg clean clothes | 0.25   |               |
| PB allocation /m³-year⁻¹ | 5.64x10⁸ | See Table S7. |
| Demand /kg clean clothes-year⁻¹ | 4.23x10¹⁰ | UK (13). |
| PwES                   | 52%    |               |
Table S13. Other impacts. Relevant to Fig. 3. Function and demand described in Table S1. Not ringfencing agriculture (P method, Eq. (S2)).

| Impact                          | Impact                  | PB allocation   | PwES |
|--------------------------------|-------------------------|-----------------|------|
| Land use 2.13E-13 %change-year | 6.96E-3 %change         | 22%             |
| Energy imbalance 1.70E-13 Wm\(^2\)-year | 2.78E-4 Wm\(^2\)     | 430%            |
| CO\(_2\) concentration 1.25E-11 ppm CO\(_2\)-year | 2.00E-2 ppm CO\(_2\) | 441% |
| Atmospheric aerosol loading 2.11E-15 optical depth-year | 3.06E-5 optical depth | 49%  |
| Stratospheric ozone depletion 2.74E-16 Dobson unit-year | 4.18E-3 Dobson units | 0.05% |
| Ocean acidification 3.82E-14 mol-year | 1.92E-4 mol | 140% |
| Phosphorus flows 1.62E-13 Tg | 1.73E-3 Tg/year | 66% |
| Nitrogen flows 3.79E-12 Tg | 1.73E-2 Tg/year | 155% |

Table S14. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient Türkiye washing machine. Relevant to Fig. 4. Ringfencing agriculture (P/A method, Eq. (S1), single wash version).

| Variable                     | Value     | Scope                   |
|-------------------------------|-----------|-------------------------|
| Impact /m\(^3\)              | 0.0836    | See Data S1 and S6.     |
| Service /wash cycles          | 1         |                         |
| PB allocation /m\(^3\)-year\(^{-1}\) | 8.46E8    | "                       |
| Demand /wash cycles-year\(^{-1}\) | 4.86E9    | "                       |
| PwES                          | 48%       |                         |

Table S15. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient Australia washing machine. Relevant to Fig. 4. Ringfencing agriculture (P/A method, Eq. (S1), single wash version).

| Variable                     | Value     | Scope                   |
|-------------------------------|-----------|-------------------------|
| Impact /m\(^3\)              | 0.0376    | See Data S1 and S6.     |
| Service /wash cycles          | 1         |                         |
| PB allocation /m\(^3\)-year\(^{-1}\) | 2.43E8    | "                       |
| Demand /wash cycles-year\(^{-1}\) | 2.43E9    | "                       |
| PwES                          | 38%       |                         |
Table S16. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient Japan washing machine. Relevant to Fig. 4. Ringfencing agriculture (P/A method, Eq. (S1), single wash version).

| Variable                          | Value  | Scope                     |
|-----------------------------------|--------|---------------------------|
| Impact /m³                        | 0.0348 | See Data S1 and S6.       |
| Service /wash cycles              | 1      |                           |
| PB allocation /m³·year⁻¹           | 1.15E9 | “                         |
| Demand /wash cycles·year⁻¹         | 2.77E10| “                         |
| PwES                              | 84%    |                           |

Table S17. Population estimates for 2016. Relevant to Fig. 2, Fig. 4, and Fig. 5. Sourced from UN data (22).

| Region | Population (of world population) |
|--------|----------------------------------|
| UK     | 66,297,994 (0.89%)               |
| TR     | 79,827,868 (1.97%)               |
| AU     | 24,262,710 (0.33%)               |
| JP     | 127,763,267 (1.71%)              |
| World  | 7,464,021,934 (100%)             |

Table S18. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient UK washing machine. Relevant to Fig. 5. Ringfencing agriculture (E/A method, Eq. (S3)).

| Variable                          | Value  | Scope                     |
|-----------------------------------|--------|---------------------------|
| Impact /m³                        | 0.0435 | See Data S1 and S7.       |
| Service /wash cycles              | 1      |                           |
| PB allocation /m³·year⁻¹           | 3.43E7 | “                         |
| Demand /wash cycles·year⁻¹         | 7.05E9 | “                         |
| PwES                              | 894%   |                           |

Table S19. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient Türkiye washing machine. Relevant to Fig. 5. Ringfencing agriculture (E/A method, Eq. (S3)).

| Variable                          | Value  | Scope                     |
|-----------------------------------|--------|---------------------------|
| Impact /m³                        | 0.0836 | See Data S1 and S7.       |
| Service /wash cycles              | 1      |                           |
| PB allocation /m³·year⁻¹           | 1.94E8 | “                         |
| Demand /wash cycles·year⁻¹         | 4.86E9 | “                         |
| PwES                              | 210%   |                           |
Table S20. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient Australia washing machine. Relevant to Fig. 5. Ringfencing agriculture (E/A method, Eq. (S3)).

| Variable                  | Value  | Scope                  |
|---------------------------|--------|------------------------|
| Impact /m³               | 0.0376 | See Data S1 and S7.    |
| Service /wash cycles     | 1      |                        |
| PB allocation /m³-year⁻¹ | 1.21E7 | "                      |
| Demand /wash cycles-year⁻¹ | 2.43E9 | "                      |
| PwES                      | 753%   |                        |

Table S21. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient Japan washing machine. Relevant to Fig. 5. Ringfencing agriculture (E/A method, Eq. (S3)).

| Variable                  | Value  | Scope                  |
|---------------------------|--------|------------------------|
| Impact /m³               | 0.0348 | See Data S1 and S7.    |
| Service /wash cycles     | 1      |                        |
| PB allocation /m³-year⁻¹ | 7.30E7 | "                      |
| Demand /wash cycles-year⁻¹ | 2.77E10 | "                      |
| PwES                      | 1324%  |                        |

Table S22. Performance-weighted Environmental Sustainability (cf_PwES) with respect to freshwater use of an efficient UK washing machine. Relevant to Fig. 5. Ringfencing agriculture (P/A method, Eq. (S1)) and modifying freshwater use into water scarcity footprint using AWARE factors.

| Variable                  | Value  | Scope                  |
|---------------------------|--------|------------------------|
| Impact /m³-equivalents    | 0.0569 | See Data S1 and S7.    |
| Service /wash cycles     | 1      |                        |
| PB allocation /m³-year⁻¹ | 5.64E8 | "                      |
| Demand /wash cycles-year⁻¹ | 7.05E9 | "                      |
| cf_PwES                   | 71%    |                        |

Table S23. Performance-weighted Environmental Sustainability (cf_PwES) with respect to freshwater use of an efficient Türkiye washing machine. Relevant to Fig. 5. Ringfencing agriculture (P/A method, Eq. (S1)) and modifying freshwater use into water scarcity footprint using AWARE factors.

| Variable                  | Value  | Scope                  |
|---------------------------|--------|------------------------|
| Impact /m³-equivalents    | 1.8480 | See Data S1 and S7.    |
| Service /wash cycles     | 1      |                        |
| PB allocation /m³-year⁻¹ | 8.46E8 | "                      |
| Demand /wash cycles-year⁻¹ | 4.86E9 | "                      |
| cf_PwES                   | 1061%  |                        |
**Table S24. Performance-weighted Environmental Sustainability (cf_PwES) with respect to freshwater use of an efficient Australia washing machine.** Relevant to Fig. 5. Ringfencing agriculture (P/A method, Eq. (S1)) and modifying freshwater use into water scarcity footprint using AWARE factors.

| Variable                  | Value     | Scope               |
|---------------------------|-----------|---------------------|
| Impact /m³-equivalents    | 0.9438    | See Data S1 and S7. |
| Service /wash cycles      | 1         |                     |
| PB allocation /m³-year⁻¹  | 2.43E8    | "                   |
| Demand /wash cycles-year⁻¹| 2.43E9    | "                   |
| cf_PwES                   | 943%      |                     |

**Table S25. Performance-weighted Environmental Sustainability (cf_PwES) with respect to freshwater use of an efficient Japan washing machine.** Relevant to Fig. 5. Ringfencing agriculture (P/A method, Eq. (S1)) and modifying freshwater use into water scarcity footprint using AWARE factors.

| Variable                  | Value     | Scope               |
|---------------------------|-----------|---------------------|
| Impact /m³-equivalents    | 0.0226    | See Data S1 and S7. |
| Service /wash cycles      | 1         |                     |
| PB allocation /m³-year⁻¹  | 1.15E9    | "                   |
| Demand /wash cycles-year⁻¹| 2.77E10   | "                   |
| cf_PwES                   | 54%       |                     |

**Table S26. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient UK washing machine (clothes mass basis, 1 small wash cycle).** Relevant to Fig. 2. Ringfencing agriculture (P/A method, Eq. (S1)).

| Variable                  | Value     | Scope               |
|---------------------------|-----------|---------------------|
| Impact /m³                | 0.0435    | Efficient           |
| Function /kg clean clothes| 3         | UK (13).            |
| PB allocation /m³-year⁻¹  | 5.64x10⁸  |                     |
| Demand /kg clean clothes-year⁻¹| 4.23x10¹⁰| UK (13).            |
| PwES                      | 109%      |                     |

**Table S27. EU scale assessment washing machine use.** Accompaniment to Figure S6. Data reinterpreted to represent the variables of a Performance-weighted Environmental Sustainability (PwES) calculation for freshwater use.

| Variable                  | Value     | Source or scope    |
|---------------------------|-----------|--------------------|
| Impact /m³                | 1.55 x10⁹| Ryberg et al. (3). |
| PB allocation (relative)  | 0.007%    | EU allocation (3). |
| PB allocation /m³-year⁻¹  | 2.80x10⁸  |                    |
| Demand /wash cycles-year⁻¹| 3.43x10¹⁰| EU (23).           |
| PwES                      | 554%      |                    |
Table S28. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an efficient UK washing machine. Ringfencing agriculture (modified P/A method, Eq. (S5)). Cheaper washing machine model with normal lifespan. Use Data S1 to calculate using FCE allocation option.

| Variable                      | Value       | Scope       |
|-------------------------------|-------------|-------------|
| Impact /m³                   | 0.0435      | Efficient   |
| Function /wash cycles         | 1           |             |
| PB allocation /m³-year⁻¹      | 3.71x10⁷    |             |
| Demand /wash cycles-year⁻¹    | 7.05x10⁹    | UK (13).    |
| PwES                          | 827%        |             |

Table S29. Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use of an inefficient UK washing machine. Ringfencing agriculture (P/A method, Eq. (S1)). Planetary boundary (PB) allocation adjusted by 2019 population data and demand adjusted by increase in UK households.

| Variable                      | Value       | Scope       |
|-------------------------------|-------------|-------------|
| Impact /m³                   | 0.0435      | Efficient   |
| Service /wash cycles          | 1           |             |
| PB allocation /m³-year⁻¹      | 5.56x10⁸    |             |
| Demand /wash cycles-year⁻¹    | 7.23x10⁹    | UK (13).    |
| PwES                          | 57%         |             |

Table S30. Theoretical Performance-weighted Environmental Sustainability (PwES) with respect to freshwater use for a UK washing machine in order to be considered sustainable using an economic weighting on the planetary boundary allocation. Ringfencing agriculture (E/A method, Eq. (S3)).

| Variable                      | Value       | Scope       |
|-------------------------------|-------------|-------------|
| Impact /m³                   | 0.0048      | Theoretical maximum. |
| Service /wash cycles          | 1           |             |
| PB allocation /m³-year⁻¹      | 3.43E7      |             |
| Demand /wash cycles-year⁻¹    | 7.05E9      | UK (13).    |
| PwES                          | 99%         |             |
Note S1. Calculating the function variable.

This explanatory Note is relevant to Fig. 1.

The function of a product is defined by the societal need that is satisfied. Examples include the calories provided by food, the energy delivered by a solar panel over its lifespan, the mileage covered by the warranty of a car, or a health treatment (drug dose equivalents or number of medical examinations). The function of the product must be quantifiable and related to the demand category (demand has additional units of per year when compared to function). The function of packaging is based on its contents.

For reusable items, the function over the product’s lifespan should ordinarily be considered. An exception was made for the Performance-weighted Environmental Sustainability (PwES) of a washing machine as water use is generally proportional to the number of wash cycles within the scope of the assessment (the exception being the water used in manufacturing the washing machine). The cumulative function of a washing machine is the total number of wash cycles performed in its lifespan. However, function is defined, the environmental impact data must represent the operation of the product. Services and activities, such as washing clothes, can require multiple products (e.g. a washing machine and detergent). Ideally, function is calculated using the guaranteed lifespan provided by the product’s warranty. For products not typically issued with a warranty, the expected or average lifespan for that product can be used. Product lifespans are routinely estimated for life cycle assessments.
Note S2. Calculating the demand variable.

This explanatory Note is relevant to Fig. 1.

The annual demand for the function performed by a product is required to calculate Performance-weighted Environmental Sustainability (PwES). The calculated demand for a function should match the scope of the planetary boundary allocation and have units that correspond to the function that is provided by the product. It follows that demand must be quantifiable. Examples include electricity use in a region, food consumption in nutrients, and hours of internet access. Future projections can be calculated using estimated demand and population size.

Demand should not be measured by the mass or number of products sold per annum. This would mean that function is defined as 1 product, and the PwES metric then only relates to an average value (equivalent to a regional or global scale sustainability assessment). The benefits of products with extended lifespans or improved efficiency cannot be assessed in this way. As an example, vehicles should be assessed in terms of distance travelled and demand for transportation, not vehicles sold.

For some products it is difficult to define demand without resorting to mass or number of units. Demand for furniture or artwork can be easily quantified as items sold per annum from market data, but to define demand for these items in terms of their function is more challenging. The aesthetic or emotional significance of some articles is more important than their practical function. Future advances to how we measure and encourage well-being may be applicable to product-level sustainability assessments, replacing the more tangible function and demand variables that are presently used in PwES. At this time, PwES is only applicable if demand can be quantified and successfully allocated a share of the planetary boundaries, whilst also permitting all other activities a planetary boundary allocation on the same basis.
Note S3. Environmental impacts.

This explanatory Note is relevant to Fig. 1.

Many products will create environmental impacts in manufacturing and in use. The scope of the assessment dictates the environmental impact attributed to a product, which shall match the scope used to define the planetary boundary allocation. Environmental impacts at all stages of the life cycle can contribute to Performance-weighted Environmental Sustainability (PwES). Environmental impact data is available in life cycle inventories, and so manufacturers can reinterpret LCA data as PwES values for different environmental impacts. Only environmental impacts that have a corresponding planetary boundary can be considered. Specifically, only blue water use (surface and groundwater) should be included in PwES calculations because the planetary boundary relates to blue water use (interchangeably called freshwater) only.
Note S4. Planetary boundary allocation.

This explanatory Note is relevant to Fig. 1.

The planetary boundary in a Performance-weighted Environmental Sustainability (PwES) calculation must be interpreted with units equal to the environmental impact but also divided by time (typically years, as to match the temporal units of the demand category). Therefore, the freshwater use planetary boundary must be described as m³/year (or equivalent), and the land use planetary boundary described in m² (or equivalent, because in this case the corresponding land use environmental impact has units of m²-year to account for how long the land is in use). The climate change planetary boundary (as measured by atmospheric carbon dioxide concentration) is set at 350 ppm,¹ with a safe operating space of 72 ppm.³ To be applicable to PwES, a sustainable limit of carbon dioxide that can be released to the atmosphere must be defined as a flux (i.e. a sustainable mass quantity of carbon dioxide emissions per year). A climate change safe operating space has been proposed in the required terms of annual CO₂ emissions by mass but values vary between sources.²,²⁴,²⁵ Springmann et al. offer a sustainable limit to agricultural emissions of CO₂-equivalents (methane and nitrous oxide but excluding CO₂ itself) of 4.7 gigatonnes per year.¹⁹

It is important to ensure the planetary boundary (PB) allocation (specifically the safe operating space) corresponds to the demand category implemented in any PwES calculation. If the demand variable represents that of a region, and not global demand, then the planetary boundary can be downscaled 'equal per capita' according to population (P). An additional economic weighting can be introduced as an 'ability-to-pay' coefficient (α).²⁶ Finally, it is necessary to establish what proportion of a planetary boundary should be dedicated to a particular function. Final consumption expenditure (FCE) or gross value added (GVA) can be used. Incorporating household activities is recommended.¹⁶ Methods are given as Equations (S1-5).

By population and sector using GVA with agricultural reservation (P/A method):

\[
P_B^{\text{impact category}} = (P_B^{\text{impact category}} - P_B^{\text{impact category, agriculture}}) \cdot \frac{P_{\text{region}}}{P_{\text{global}}} \cdot \frac{GVA_{\text{sector region}}}{GVA_{\text{total region}} - GVA_{\text{agriculture region}}}\]  

By population and sector using GVA without agricultural reservation (P method):

\[
P_B^{\text{impact category}} = P_B^{\text{impact category}} \cdot \frac{P_{\text{region}}}{P_{\text{global}}} \cdot \frac{GVA_{\text{sector region}}}{GVA_{\text{total region}}}\]  

By wealth of region and sector using GVA with agricultural reservation (E/A method):

\[
P_B^{\text{impact category}} = (P_B^{\text{impact category}} - P_B^{\text{impact category, agriculture}}) \cdot \frac{p_{\text{region}}}{p_{\text{global}}} \cdot \frac{GD_P^{\text{per capita}}_{\text{global}}}{GD_P^{\text{per capita}}_{\text{region}}} \cdot \frac{GD_A^{\text{per capita}}_{\text{region}}}{GD_A^{\text{per capita}}_{\text{agriculture region}}} \cdot \frac{GVA_{\text{sector region}}}{GVA_{\text{total region}}}\]  

By wealth of region and sector using GVA without agricultural reservation (E method):

\[
P_B^{\text{impact category}} = P_B^{\text{impact category}} \cdot \frac{p_{\text{region}}}{p_{\text{global}}} \cdot \frac{GD_P^{\text{per capita}}_{\text{global}}}{GD_P^{\text{per capita}}_{\text{region}}} \cdot \frac{GD_A^{\text{per capita}}_{\text{region}}}{GD_A^{\text{per capita}}_{\text{agriculture region}}} \cdot \frac{GVA_{\text{sector region}}}{GVA_{\text{total region}}}\]  

By population and sector using FCE with agricultural reservation (modified P/A method):

\[
P_B^{\text{impact category}} = (P_B^{\text{impact category}} - P_B^{\text{impact category, agriculture}}) \cdot \frac{P_{\text{region}}}{P_{\text{global}}} \cdot \frac{FCE_{\text{sector region}}}{FCE_{\text{total region}} - FCE_{\text{food region}}}\]
Note S5. Comparison to other sustainability assessments.

Performance-weighted Environmental Sustainability (PwES, see Fig. 1 for an annotated equation) adds to the emerging class of ‘absolute’ sustainability assessments. This refers to life cycle assessments (LCAs) modified by carrying capacity, meaning the maximum tolerable impact of an activity that does not cause irreparable damage to the environment (known as the safe operating space). Figure S1 illustrates that while relative sustainability assessment is a mature field and applicable at various scales, far fewer absolute sustainability methodologies are available, particularly for individual products. The introduction of the function to demand ratio to fairly differentiate between products is not a linear scaling factor to convert regional assessments into product-level assessments. It has this effect only if all products have equal performance (Figure S2). Function is defined by product design and user habits and is variable. To illustrate how PwES can be informative to product designers and engaged consumers, three hypothetical case studies are provided comparing PwES to an equivalent regional assessment (e.g., share of safe operating space, SoSOS). The first example represents a situation where all products possessing the same function have identical performance and environmental impact (Figure S2). The variables are not defined because this is a generic case study. If PwES equals 115% then so will the regional assessment. More realistically, a variety of products will contribute to demand, each functioning to a different degree of efficiency and with different lifespans. This could be due to how long the product can be used for, or for the example of transport, a bus provides a greater function in terms of the passenger-distances achieved than a car over its lifespan. The left of Figure S3 shows a typical frequency of products, the most efficient product providing three times the function of the least efficient. If the environmental impact is the same for each product, PwES values decrease as function increases. About one third the products in this hypothetical scenario are considered sustainable with respect to the environmental impact under consideration. The remainder are unsustainable. The equivalent regional-scale assessment determines that this activity is unsustainable at 115% of the permissible environmental impact. This might imply a uniform policy of emissions reductions to all products is needed. This would tolerate unsustainable products operating with low efficiency, compensated by very efficient and low emissions products. PwES indicates which products are unsustainable and what performance improvements (greater function or less emissions) are required.

Figure S4 represents a complex scenario in which emissions increase non-linearly with function. If a product is more efficient it may consume more energy to operate, and so function and environmental impact increases. The manufacture of more durable products may also incur higher environmental impacts. The greatest environmental impact is five times greater than the lowest. The function range provided is the same as in Figure S3, but the conclusions have been reversed. The highest PwES value actually belongs to the most efficient product, and only the two least efficient products are considered sustainable. This is because the environmental impact incurred to improve the function increases at a greater rate than can be compensated for. This situation is undesirable for the consumer. In reality, products that incur the majority of their environmental impact in the manufacturing phase will become more sustainable with improved function (typically via an extended lifespan). If the majority of the environmental impact is a result of using the product, greater function through extended lifespan will have a minimal effect on PwES values. In this case, the product designer should attempt to reduce the environmental impact per use, rather than increase the number of uses. As in all sustainability assessment, an action to reduce one particular environmental impact will often be shown to increase others, and so any actions need to be thoroughly considered. Product design, technological advances, and instructions for consumers can be determined with the goal that PwES values for each environmental impact are below 100%. Such specific guidance requires the product-level scope of PwES.
Note S6. Laundry sustainability.

The Performance-weighted Environmental Sustainability (PwES) of washing machines with different water efficiencies have been calculated with an estimate of 2016 demand in four countries to be consistent with the economic data used to allocate a portion of the freshwater use planetary boundary from the same year. The data in Fig. 2 is tabulated in Table S1 to Table S4 and Supplemental Data S3 (also see Data S1 for other calculations and all data sources, hosted at https://doi.org/10.5281/zenodo.7240305). The scope is shown in Figure S5. This Note is also relevant to Fig. 6.

Freshwater use PwES was also obtained for the lifespan of the washing machine to show the result is the same as performing the calculation on a single wash basis (Table S10). This assumes a 6 kg load household washing machine is used 260.1 times a year and has a lifespan of 12.09 years,\textsuperscript{13} and water usage is consistent. The more precise function and demand categories based on the quantity of clothes washed (by mass) have been used in Table S11 (again, no change to the freshwater use PwES value occurs). The equivalent regional scale assessment,\textsuperscript{3} has been recalculated in the form of the PwES metric in Table S27 and Figure S6, in which the planetary boundary allocation was based on the GVA of detergent only. Gross value added (GVA) data for the UK is provided in Table S6 and population estimates are in Table S5. Their application to downsizing the freshwater use planetary boundary is summarized in Table S7. The alternative final consumption expenditure (FCE) allocation method is used in Table S28. The typical cost of electricity and water to operate the washing machine, and the price of detergent was obtained from Ryberg et al. (2018).\textsuperscript{3} This was converted to an annual cost based on the average number of annual wash cycles and then represented as a proportion of total household FCE minus FCE on food (so to be consistent with the subtraction of agriculture from the planetary boundary allocation, see Eq. (S5)). Average UK economy data was used for this purpose, converted to Euro. To this, the cost of the washing machine was added, at £184.99-£316.58, divided by the years of use. An extended use scenario of 30.8 years rather than 12.09 years may also be considered in Supplemental Data S1 (https://doi.org/10.5281/zenodo.7240305). The FCE allocation method (Eq. (S5)) is not recommended because expensive versions of products receive a larger planetary boundary allocation than equivalent low price products.

Data for Fig. 3 is derived from Ryberg et al. (2018),\textsuperscript{3} and provided in Supplemental Data S5 (https://doi.org/10.5281/zenodo.7240305, also Table S13). Data for Fig. 4 is in Supplemental Data S6 (https://doi.org/10.5281/zenodo.7240305). The PwES calculations follow the same principles as the UK study but freshwater use, demand, and the variables for the allocation of the planetary boundaries are based on different regions (Table S14 to Table S16). All data is found in Supplemental Data S1 (https://doi.org/10.5281/zenodo.7240305). Data for Fig. 5 is in Supplemental Data S7 (https://doi.org/10.5281/zenodo.7240305). The PwES calculations are modified, either by an economic weighting (Table S18 to Table S21),\textsuperscript{18} or by regional water scarcity (Table S22 to Table S25),\textsuperscript{27} using established methods. Data for Fig. 6 is in Supplemental Data S8 (https://doi.org/10.5281/zenodo.7240305). The standard UK annual assessment is modified to the scope of London on a monthly basis. The freshwater use planetary boundary is reduced according to a per capita basis (Eq. (S1)) and the monthly carrying capacity is based on the number of days in the month compared to the year. Monthly demand is derived from the data of Zimmermann et al. (2012).\textsuperscript{28}
Note S7. Uncertainty analysis and sensitivity analysis of laundry case study.

The washing machine Performance-weighted Environmental Sustainability (PwES) freshwater use case study has been subjected to an error analysis (based on the study summarized in Fig 2). The error associated with the published data used in this work is usually reported as a percentage range. This has been reinterpreted as the bounds of the 95% confidence level of a normal distribution, or a logarithmic normal distribution when appropriate (with the following exceptions, see Table S8). Because the freshwater use planetary boundary is difficult to quantify, assumed to be between 4,000-6,000 km$^3$ per year,$^1$ the lower end of this range is taken as the default value. To account for the possibility the planetary boundary is higher, two probability distributions have been used. The first assumes each value between 4,000-6,000 km$^3$ per year is equally likely. The second is an exponential function ($e^{-x}$), whereby low values of the freshwater use planetary boundary are considerably more probable than high values. The sustainable freshwater use limit allocated to agriculture was calculated by Springmann et al. to be 1,980 ($\pm 1,200$) km$^3$ per year.$^1$ This probability can be modelled as a normal distribution, and alternatively, a second scenario in which each value within range was assumed to be equally as likely.

To visualize the uncertainty analysis, a random number between 0 and 1 was generated to represent the probability of a variable having a particular value (according to its cumulative probability distribution). This was performed 500 times for each variable. Probability distributions are given in the Supplemental Data S2 (https://doi.org/10.5281/zenodo.7240305). Additionally, the sensitivity of PwES values to changes to the magnitude of the input variables was investigated using sensitivity coefficients ($S_{coef}$). The same methodology was used as Ryberg et al. (2018).$^3$ As shown in Eq. (S6), $IS_0$ is the PwES value resulting when $v_0$ is the variable under investigation. $\Delta IS$ is the difference between $IS_0$ and the PwES value when the input variable is perturbed. $\Delta v$ is the difference between the default variable and its perturbed value. All the variables were perturbed by 10%.

Eq. (S6) \[ S_{coef} = \frac{\Delta IS}{IS_0} / \frac{\Delta v}{v_0} \]

$|S_{coef}|$ is 1 when there is a linear relationship between the magnitude of the variable and the resulting PwES value (e.g., the demand category). Alternatively, when the larger perturbed input reduces the final PwES value (e.g., the function category), $|S_{coef}|$ is 0.91 (i.e., the inverse of 1.1). For the assessment of washing machine freshwater use, the most significant $|S_{coef}|$ value is obtained by perturbing the freshwater use planetary boundary ($|S_{coef}| = 1.65$, see Table S9). This variable is also the most significant in the uncertainty analysis.
Note S8. Laundry sustainability: Hand wash alternative.

To supplement the main washing machine case study, clothes washing by alternative means is included here. The full data is provided in Supplemental Data S4 (https://doi.org/10.5281/zenodo.7240305). The planetary boundary allocation and demand category is based on unpaid household laundry in the UK in 2016 (ringfencing an allocation of planetary boundaries for agriculture, P/A method, see Eq. (S1)). This means that laundrette use, as a paid service, is excluded, but hand washing clothes is within scope. The four Performance-weighted Environmental Sustainability (PwES) variables are derived in the same way as the washing machine case study. Washing clothes in a stream, river, or lake has a freshwater use PwES value of 0% because the water use is non-consumptive, meaning it is directly returned to its original source. However, other environmental impacts due to using a detergent are significant (see Fig. 3 for more information). This example is based on hand washing clothes at home. This assessment is only possible because the GVA-equivalents of household services are valued and included in the planetary boundary allocation.

Unlike a washing machine, hand washing clothes does not use a well-defined volume of water. For the purpose of this study, either a small basin containing 5 L of water or a large basin containing 10 L of water is used to wash 1 light jumper (0.25 kg) or 1 kg of mixed clothes at home (with the same water supply as a washing machine). Using 5 L of water to wash 1 jumper has a freshwater use PwES value of 52% (Table S12). Additional rinsing water of up to 10 L has also been considered (Data S4).
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