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A good life for all within planetary boundaries

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Humanity faces the challenge of how to achieve a high quality of life for over 7 billion people without destabilizing critical planetary processes. Using indicators designed to measure a 'safe and just' development space, we quantify the resource use associated with meeting basic human needs, and compare this to downscaled planetary boundaries for over 150 nations. We find that no country meets basic needs for its citizens at a globally sustainable level of resource use. Physical needs such as nutrition, sanitation, access to electricity and the elimination of extreme poverty could likely be met for all people without transgressing planetary boundaries. However, the universal achievement of more qualitative goals (for example, high life satisfaction) would require a level of resource use that is 2–6 times the sustainable level, based on current relationships. Strategies to improve physical and social provisioning systems, with a focus on sufficiency and equity, have the potential to move nations towards sustainability, but the challenge remains substantial.

This Article addresses a key question in sustainability science: what level of biophysical resource use is associated with meeting people's basic needs, and can this level of resource use be extended to all people without exceeding critical planetary boundaries? To answer this question, we analyse the relationships between 7 indicators of national environmental pressure (relative to biophysical boundaries) and 11 indicators of social outcomes (relative to sufficiency thresholds) for over 150 countries. Our study measures national performance using a 'safe and just space' framework[1,2] for a large number of countries, and provides important findings on the relationships between resource use and human well-being.

A safe and just space

There have been two recent, complementary advances in defining biophysical processes, pressures and boundaries at the planetary scale. The first is the planetary boundaries framework, which identifies nine boundaries related to critical Earth-system processes[3]. The boundaries jointly define a 'safe operating space', within which it is argued the relatively stable conditions of the Holocene may be maintained[4]. Of the seven measured planetary boundaries, four are currently transgressed (biosphere integrity, climate change, biogeochemical flows and land-system change)[3].

The second advance is the estimation of environmental 'footprint' indicators for multiple types of biophysical resource flows. Footprint indicators associate specific environmental pressures (for example, CO_2 emissions, material extraction, freshwater appropriation) with the consumption of goods and services[5]. This approach assigns responsibility for embodied resource use to final consumers, and includes the effects of international trade.

We combine these two approaches to measure sustainability at the national scale, by comparing national consumption-based environmental footprints to 'downscaled' planetary boundaries[6]. The nascent literature proposes a number of different ways that planetary boundaries could theoretically be downscaled to national equivalents[7], taking into account factors such as geography, international trade and equity[8]. Some studies apply a top-down approach that distributes shares of each planetary boundary to countries based on an allocation formula[9–11], while others apply a bottom-up approach that associates local or regional environmental limits with each planetary boundary[12,13].

Within our analysis we apply a top-down approach that distributes shares of each planetary boundary among nations based on current population (a per capita biophysical boundary approach). While the environmental justice literature emphasizes the need for differentiated responsibilities in practice[14], a per capita approach allows us to explore what quality of life could be universally achieved if resources were distributed equally. It is an important question to address given that it is often claimed that all people could live well if only the rich consumed less, so that the poor could consume more[2,15]. We acknowledge that an annual per capita boundary may not be an appropriate way to manage resources that are geographically and temporally bounded (for example, freshwater use, where river-basin geography and a monthly timescale may be more appropriate in practice[16]). Moreover, a deeper understanding of equity may require some notion of shared responsibility between producers and consumers[17].

Here, we adopt a human needs-based approach to defining and measuring social outcomes, drawing on the work of Max-Neef[18] and Doyal and Gough[19]. Human needs theory argues that there are a finite number of basic human needs that are universal, satiable and non-substitutable. 'Need satisfiers' can vary between individuals and cultures, but arguably have certain universal characteristics that may be measured empirically[20].

The theory of human needs developed by the above authors underpins the safe and just space (SJS) framework proposed by Raworth[1], and described in her book *Doughnut Economics*[2]. The framework combines the concept of planetary boundaries with the complementary concept of social boundaries. It visualizes sustainability in terms of a doughnut-shaped space where resource use is high enough to meet people's basic needs (the inner boundary), but not so high as to transgress planetary boundaries (the outer boundary).

The SJS framework includes 11 social objectives, which were selected by Raworth based on a comprehensive text analysis of government submissions to the Rio+20 conference. The objectives reflect the main social goals mentioned in the majority of submissions, and thus align well with contemporary policy, including the social objectives in the United Nations Sustainable Development Goals (SDGs)[21]. The SJS framework also has important precedents in the ecological economics literature, namely the objectives of sustainable scale, fair distribution and efficient allocation[22].

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We argue that the SJS framework operationalizes the concept of 'strong sustainability'[23]. It requires that stocks of critical natural capital be maintained (via the planetary boundaries requirement), while at the same time requiring that stocks of critical human and social capital also be maintained (the basic needs requirement). What the SJS framework lacks, however, is a conceptualization of how resource use and social outcomes are linked. Understanding and quantifying this link is critical for determining whether it is actually possible for countries to operate within the safe and just space.

Analytic framework

Our analytic framework (Fig. 1) is based on the Ends–Means Spectrum[24,25], which we have previously used for measuring strong sustainability[26,27]. Importantly, the framework does not imply a one-way causal link between resource use and social outcomes; instead, it is intended to show that social outcomes are dependent on healthy, functioning ecosystems and the resources that they provide. Feedback loops run both ways, and society may mitigate or adapt to the transgression of planetary boundaries, thus changing the underlying system structure or its parameters[28].

Here, we extend the framework by (i) using a basic needs approach to conceptualize social outcomes within nations (separating between need satisfiers and human well-being), and (ii) representing the link between resource use and social outcomes in terms of 'provisioning systems'. For our purposes, provisioning systems comprise both physical and social systems; the former include networks of physical infrastructure, technologies and their efficiencies[29], while the latter encompass government institutions, communities and markets[30]. Provisioning systems mediate the relationship between biophysical resource use and social outcomes. For example, different forms of transportation infrastructure (railways versus highways) generate similar social outcomes at very different levels of resource use. Within our analysis, we do not attempt to characterize different types of provisioning system or their effects on the relationship between resource use and social outcomes—this remains a complex challenge for Earth-system researchers going forward[31]. However, we do quantify the resource use associated with meeting basic needs in different countries, thus giving an indication of current possibilities.

Although existing analyses have quantified the links between social performance and biophysical indicators such as energy use[32], greenhouse gas emissions[33] and ecological footprint[34], these analyses have not considered the implications of planetary boundaries on social outcomes. Two studies have considered biophysical boundaries and social outcomes using the SJS framework for specific countries and sub-regions (South Africa[12] and two regions of China[13]), while a third study has applied the framework to five cities[35]. However, these studies have been limited in their geographical scope, and they have not quantified the links between the biophysical boundaries and social thresholds, which a number of authors have argued need to be better understood[8,11]. In short, existing studies have either quantified the limits (but not the links) or the links (but not the limits). This Article addresses this gap in the literature by investigating what level of biophysical resource use is associated with meeting people's basic needs, and whether this level of resource use can be extended to all people without exceeding critical planetary boundaries.

Biophysical boundaries and social thresholds

We downscale four planetary boundaries (climate change, land-system change, freshwater use and biogeochemical flows) to per capita equivalents, and compare these to footprint indicators at the national scale. In addition, we include two separate footprint indicators (ecological footprint and material footprint) and compare these to their suggested maximum sustainable levels[5]. The ecological footprint and material footprint are not part of the planetary boundaries framework, and partially overlap with the climate change indicator (they both include fossil energy as a component). However, as they are widely reported measures of environmental pressure, we include them for comparison. Since the planetary boundary for biogeochemical flows is represented by two separate indicators (nitrogen and phosphorus), seven biophysical indicators are considered in total (Table 1). All seven indicators are consumption-based measures that account for international trade.

Due to the difficulty in translating the planetary boundary for atmospheric CO_2 concentration into a meaningful per capita boundary, we base our calculations on the goal of limiting global warming to 2 °C, as emphasized in the Paris Agreement. As a measure of land-system change, we use a novel indicator, namely embodied human appropriation of net primary production (eHANPP)[36], which has been proposed as a measurable planetary boundary[37]. eHANPP measures the amount of biomass harvested through agriculture and forestry, as well as biomass that is killed during harvest but not used, and biomass that is lost due to land use change. (See Supplementary Information for a full discussion of the individual biophysical indicators.)

To assess social outcomes, we use a set of 11 social indicators that are common to studies following the SJS framework[1,12,13] and the social objectives contained in the SDGs[21]. Within our framework, these indicators include nine need satisfiers (nutrition, sanitation, income, access to energy, education, social support, equality, democratic quality and employment) and two measures of human well-being (self-reported life satisfaction and healthy life

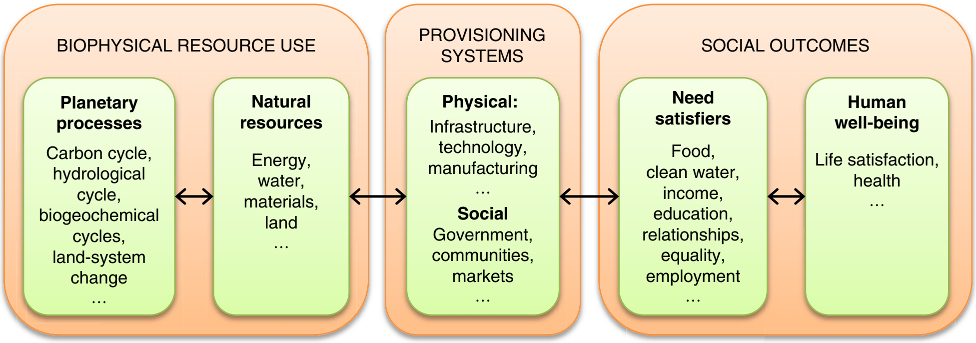

Fig. 1 | Analytic framework showing the link between planetary processes and human well-being. The framework is based on Daly's Ends–Means Spectrum[24], which Meadows proposed using to measure sustainable development[25]. Social outcomes are conceptualized in terms of a basic needs approach[18,19], while provisioning systems are seen to mediate the relationship between biophysical resource use and social outcomes.

Table 1 | Country performance with respect to per capita biophysical boundaries

Biophysical indicator	*N*	Planetary boundary	Per capita boundary	Countries within boundary (%)
CO_2 emissions	145	2 °C warming	1.61 t CO_2 yr^{-1}	34
Phosphorus	144	6.2 Tg P yr^{-1}	0.89 kg P yr^{-1}	44
Nitrogen	144	62 Tg N yr^{-1}	8.9 kg N yr^{-1}	45
Blue water	141	4,000 km^3 yr^{-1}	574 m^3 yr^{-1}	84
eHANPP	150	18.2 Gt C yr^{-1}	2.62 t C yr^{-1}	44
Ecological footprint	149		1.72 gha yr^{-1}	43
Material footprint	144		7.2 t yr^{-1}	44

N is the number of countries.

expectancy). For each of these indicators, we identify a threshold value consistent with a 'good life' for a nation's citizens (Table 2). Although the choice of the social thresholds is undoubtedly subjective, we believe each constitutes a reasonable assessment of a level of performance consistent with meeting basic needs. (See Supplementary Information for a full discussion of the individual social indicators.)

We find that the majority of the countries analysed are using resources at levels above the per capita biophysical boundaries (Table 1). The most difficult biophysical boundary to meet is climate change: only 34% of countries are within the per capita boundary for this indicator. The number of countries that are within the per capita boundaries for phosphorus, nitrogen, eHANPP, ecological footprint and material footprint is remarkably similar overall, with roughly 45% of countries within the boundary for each of these indicators. The picture is substantially better for the blue water boundary, which over 80% of countries are currently within, reflecting the fact that this boundary is not transgressed at the planetary scale. However, this result says nothing about regional water scarcity, which may result from intra-annual variability or differences in water availability across river basins. Overall, 16 countries remain within all 7 per capita biophysical boundaries, while there are 48 countries that transgress 6 or more of them (Fig. 2).

From a social perspective, the results are rather mixed (Table 2). Close to 60% of the countries analysed perform well on the social indicators related to meeting physical needs such as nutrition and access to energy, and close to 70% have eliminated poverty below the US$1.90 a day line. Countries do not perform as well on the more qualitative goals, however. Only a quarter of the countries analysed achieve sufficient outcomes on the indicators of life satisfaction and social support, while less than a fifth achieve sufficient outcomes on the indicators of democratic quality and equality. Only three countries (Austria, Germany and the Netherlands) achieve all 11 social thresholds, although an additional 7 (mostly European) countries achieve 10 of them. Thirty-five countries fail to achieve more than a single social threshold (Fig. 2).

No country performs well on both the biophysical and social indicators. In general, the more social thresholds a country achieves, the more biophysical boundaries it transgresses (Fig. 2), and vice versa. Many wealthy nations achieve the majority of the social thresholds, but at a level of resource use that is far beyond

Table 2 | Country performance with respect to social thresholds

Social indicator	*N*	Threshold	Countries above threshold (%)
Life satisfaction	134	6.5 on 0–10 Cantril ladder scale	25
Healthy life expectancy	134	65 years	40
Nutrition	144	2,700 kilocalories per person per day	59
Sanitation	141	95% of people have access to improved sanitation facilities	37
Income	106	95% of people earn above US$1.90 a day	68
Access to energy	151	95% of people have electricity access	59
Education	117	95% enrolment in secondary school	37
Social support	133	90% of people have friends or family they can depend on	26
Democratic quality	134	0.80 (approximate US/UK value)	18
Equality	133	70 on 0–100 scale (Gini index of 0.30)	16
Employment	151	94% employed (6% unemployment)	38

Within our analytic framework, life satisfaction and healthy life expectancy are classified as measures of human well-being, while the remaining nine social indicators are classified as need satisfiers. *N* is the number of countries.

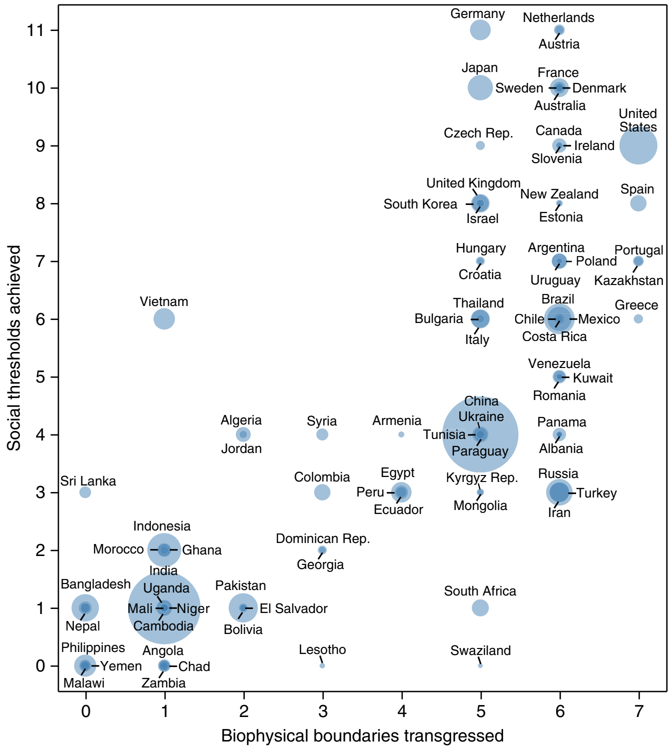

Fig. 2 | Number of social thresholds achieved versus number of biophysical boundaries transgressed for different countries (scaled by population). Ideally, countries would be located in the top-left corner. Only countries with data for all 7 biophysical indicators and at least 10 of the 11 social indicators are shown (*N* = 109).

the per capita biophysical boundaries. For example, although the United States achieves the threshold associated with a good life for 9 of the 11 social indicators, it transgresses the per capita boundary for all 7 biophysical indicators (Fig. 3a). In contrast, Sri Lanka, which does not transgress any of the biophysical boundaries, only achieves sufficient outcomes on 3 of the social indicators (Fig. 3b). Vietnam is a possible exception to the pattern, transgressing only 1 biophysical boundary (CO_2 emissions), but achieving sufficient outcomes on 6 social indicators.

In general, the more social thresholds associated with need satisfiers that a country achieves, the higher the level of human well-being, as measured by life satisfaction and healthy life expectancy (Supplementary Fig. 1). These results provide some evidence in support of the argument that human well-being is a function of both the level to which basic needs are met and the extent to which individuals are satisfied with this level[38,39]. Countries with higher levels of life satisfaction and healthy life expectancy also tend to transgress more biophysical boundaries (Supplementary Fig. 2).

Relationship between indicators

The strength of the relationship between biophysical and social indicators varies depending on the individual indicators considered (Supplementary Table 3). In general, social performance is most tightly coupled to CO_2 emissions and material footprint, and least tightly coupled to eHANPP. The weak relationship between eHANPP and the social indicators is consistent with previous work showing that eHANPP is strongly linked to population density, but not to other socioeconomic factors[40].

The social indicators most tightly coupled to resource use are secondary education, sanitation, access to energy, income and nutrition. With the exception of education, these are more closely associated with meeting physical needs than with achieving more qualitative goals (for example, social support and democratic quality). The social indicator least tightly coupled to resource use is employment.

In cases where there is a statistically significant relationship between biophysical and social indicators, the relationship is always positive (that is, higher social performance is associated with higher resource use). Moreover, the best-fit curve is generally either linear–logarithmic in form or a saturation curve (Supplementary Table 3). Both shapes suggest diminishing social returns with higher resource use. The only exception is equality, which increases linearly with resource use.

Figure 4 presents the level of resource use, relative to per capita biophysical boundaries, associated with achieving a sufficient level of performance on each social indicator. Two quantities are shown: (1) the median level of resource use of the countries closest to each social threshold, and (2) the lowest level of resource use (that is, best performance) achieved by any country that meets the social threshold.

The largest gap between current performance and the biophysical boundary occurs for CO_2 emissions, where the median level of resource use associated with a sufficient score on the social indicators ranges from about 1.5 times the biophysical boundary for nutrition and sanitation, to over 6 times this boundary for education and life satisfaction. That said, the large difference between the median and lowest levels of CO_2 emissions for some of the social thresholds (for example, education and life satisfaction) demonstrates that much more carbon-efficient provisioning systems are possible.

The median results for phosphorus and nitrogen are very similar to CO_2 emissions, although the level of resource use associated with sufficient social performance is a bit lower. For material footprint and ecological footprint, the median estimate varies less, from near the biophysical boundary to over three times this level. The least-strict biophysical boundary is blue water use, where a high level of performance can be achieved on all social indicators without transgressing the planetary boundary. This result says nothing of local water scarcity issues, however.

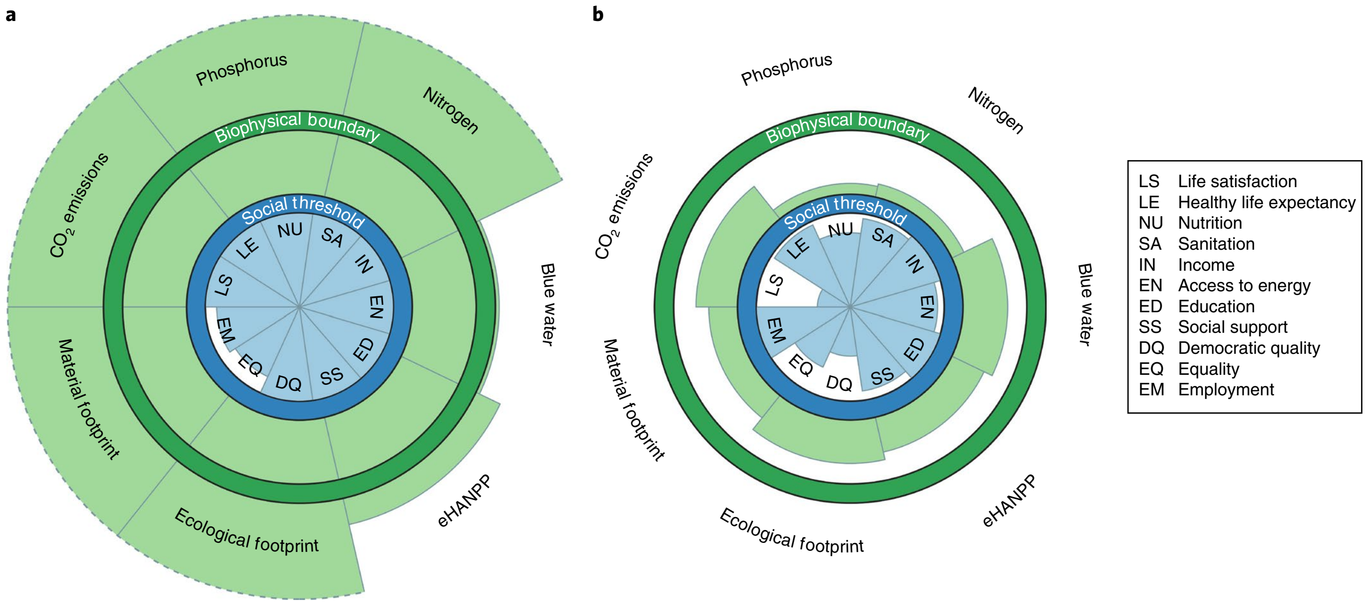

Fig. 3 | National performance relative to a 'safe and just space' for two countries. a, The United States. **b**, Sri Lanka. Blue wedges show social performance relative to the social threshold (blue circle), whereas green wedges show resource use relative to the biophysical boundary (green circle). The blue wedges start at the centre of the plot (which represents the worst score achieved by any country), whereas the green wedges start at the outer edge of the blue circle (which represents zero resource use). Both the social thresholds and biophysical boundaries incorporate a range of uncertainties, and should be interpreted as fuzzy lines. Wedges with a dashed edge extend beyond the chart area. Ideally, a country would have blue wedges that reach the social threshold and green wedges within the biophysical boundary. See Supplementary Data for data for all countries and https://goodlife.leeds.ac.uk for an interactive website that produces plots for all countries.

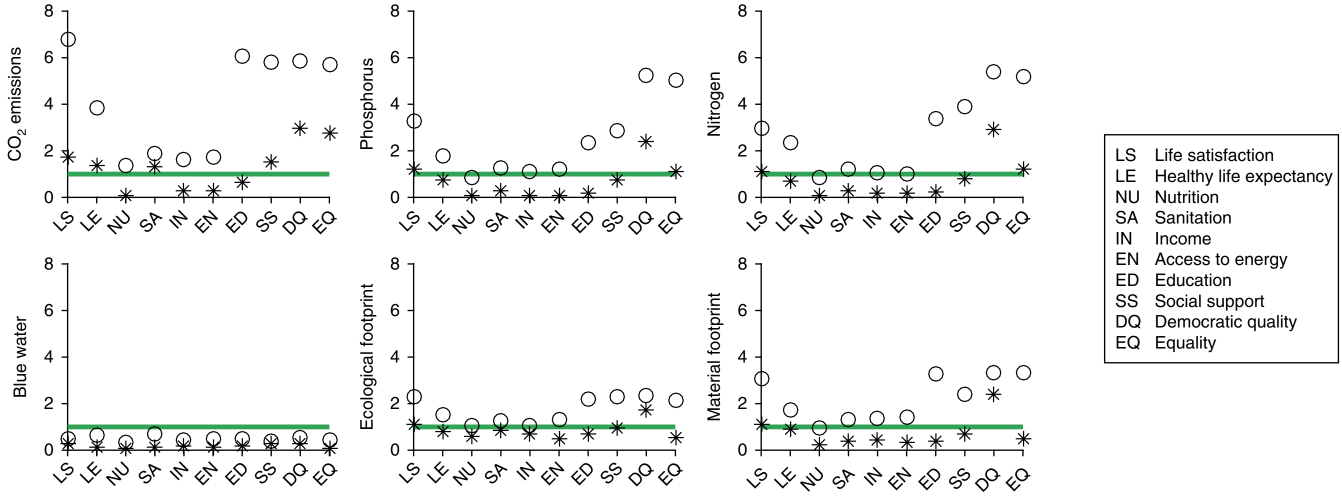

Fig. 4 | Estimated level of resource use needed to achieve a sufficient level of performance on each social indicator. Open circles indicate the median level of resource use for countries at the social threshold, whereas stars represent the lowest level of resource use (best performance) of any country achieving the threshold. Resource use is expressed relative to the per capita boundary for each biophysical indicator (green line). Relationships involving eHANPP and employment are not shown due to the low statistical significance of these relationships.

The social goals with the highest associated resource use, ranging from about two to six times the per capita biophysical boundary, are democratic quality, equality, social support, secondary education and life satisfaction. These are the more qualitative social goals, and although they are associated with high resource use, they are in general not tightly coupled to resource use. In contrast, the social goals that relate more directly to meeting physical needs (that is, nutrition, income, access to energy and sanitation) are more tightly coupled to resource use, but have much lower associated resource use in general. In fact, our results indicate that a sufficient level of performance on these four indicators could likely be achieved for all people without significantly exceeding planetary boundaries. An important exception to the overall pattern is secondary education, which is both strongly coupled to resource use and associated with high resource use.

While the median resource use values give a business-as-usual view, they may be overly pessimistic about what is possible. The best performance values show that some nations are able to achieve the social thresholds at a much lower level of resource use. These results give a sense of the possibility space for achieving the social thresholds within planetary boundaries, while also highlighting the unequal distribution of current resource use among countries. For four of the social indicators (that is, education, access to energy, income and nutrition), there is at least one country that achieves the threshold associated with a good life without transgressing any of the per capita biophysical boundaries. There is no single best-performing country, however. In general, it is a different country that performs well in each biophysical–social indicator pair. For two of the other social indicators (that is, democratic quality and life satisfaction), there is generally no country that achieves the social threshold within the biophysical boundaries (leaving aside blue water).

Discussion

If all people are to lead a good life within planetary boundaries, then our results suggest that provisioning systems must be fundamentally restructured to enable basic needs to be met at a much lower level of resource use. These findings represent a substantial challenge to current development trajectories. Given that the United Nations 'medium variant' prediction is for global population to rise to 9.7 billion people by 2050, and 11.2 billion by 2100[41], the challenge will be even greater in future if efforts are not also made to stabilize global population. It is possible that the doughnut-shaped space envisaged by Raworth[1,2] could be a vanishingly thin ring.

Physical needs (that is, nutrition, sanitation, access to energy and elimination of poverty below the US$1.90 line) could likely be met for 7 billion people at a level of resource use that does not significantly transgress planetary boundaries. However, if thresholds for the more qualitative goals (that is, life satisfaction, healthy life expectancy, secondary education, democratic quality, social support and equality) are to be universally met then provisioning systems—which mediate the relationship between resource use and social outcomes—must become two to six times more efficient.

Based on our findings, two broad strategies may help move nations closer to a safe and just space. The first is to focus on achieving 'sufficiency' in resource consumption. For most of the biophysical–social indicator pairs analysed in this study, each additional unit of resource use contributes less to social performance, particularly beyond the turning point where the estimated linear–logarithmic or saturation curves flatten out (Supplementary Table 3). Our results suggest resource use could be reduced significantly in many wealthy countries without affecting social outcomes, while also achieving a more equitable distribution among countries. A focus on sufficiency would involve recognizing that overconsumption burdens societies with a variety of social and environmental problems[42], and moving beyond the pursuit of GDP growth to embrace new measures of progress[43]. It could also involve the pursuit of 'degrowth' in wealthy nations[15], and the shift towards alternative economic models such as a steady-state economy[24,44].

Second, there is a clear need to characterize and improve both physical and social provisioning systems. Physical improvements include switching from fossil fuels to renewable energy, producing products with longer lifetimes, reducing unnecessary waste, shifting from animal to crop products, and investing in new technologies[5,29]. Remaining within the 2 °C climate change boundary is a particular challenge, requiring the majority of energy generation to be decarbonized by 2050[45]. While the cost of wind and solar energy is falling dramatically, which could lead to a major shift in infrastructure[46], the fossil fuel industry remains remarkably resilient, subsidized, and still capable of tipping us over the limit[47]. Moreover, improvements in resource efficiency are unlikely to be enough on their own, in part because more efficient technologies tend to lower costs, freeing up money that is inevitably spent on additional consumption (the so-called rebound effect)[48].

For this reason, improvements in social provisioning are also required, in particular to reduce income inequality and enhance social support. Both of these indicators are only weakly correlated with resource use in our analysis (Supplementary Table 3), but have a demonstrated positive effect on a broad range of social outcomes[49,50]. Given the high resource use associated with qualitative goals such as life satisfaction (Fig. 4), these goals may be better pursued using non-material means. The combined effects of a few social and institutional factors such as social support, generosity, freedom to make life choices and absence of corruption have been shown to explain a substantial amount of the variation in life satisfaction among countries[49].

Overall, our findings suggest that the pursuit of universal human development, which is the ambition of the SDGs, has the potential to undermine the Earth-system processes upon which development ultimately depends. But this does not need to be the case. A more hopeful scenario would see the SDGs shift the agenda away from growth towards an economic model where the goal is sustainable and equitable human well-being. However, if all people are to lead a good life within planetary boundaries, then the level of resource use associated with meeting basic needs must be dramatically reduced.

Methods

Downscaling planetary boundaries. Defining rigorous environmental boundaries in a consistent framework at local, national and planetary levels represents a significant challenge for sustainability science[7,8,12]. It has been suggested that a top-down allocation approach is more appropriate for boundaries where human activities exert a direct impact on the Earth (that is, climate change, ocean acidification, ozone depletion and chemical pollution), while a multiscale approach is more appropriate for boundaries that are spatially heterogeneous (that is biogeochemical flows, freshwater use, land-system change, biodiversity loss and aerosol loading).[8] Even with a top-down approach and a single global boundary, however, allocation is fraught with difficult ethical issues. In the context of climate change, various methods of allocating emissions budgets have been proposed. These include allocating the budget on the basis of equal individual rights (a per capita approach), historical rights (that is, 'grandfathering'), historical responsibility (that is, accounting for cumulative emissions), and sufficiency (that is, enough for a decent life)[7,51]. Regardless of which approach might be more ethically appealing, resource use still tends to be managed at the national or sub-national scale[8,10].

Although we believe that a multiscale approach would be the most appropriate method for allocating certain planetary boundaries and managing resource use in practice, within our analysis we apply a top-down approach that assigns equal shares of each planetary boundary on a per capita basis. This choice is motivated by our particular research question, namely what level of social outcomes could be universally achieved if resources were distributed equally? Or conversely, what are the resource use implications of satisfying a universal and decent quality of life? An equal allocation theoretically yields the possibility of achieving a decent life for the largest number of people. Although other allocations would allow some people to lead a higher quality of life (for example, those living in countries with large resource endowments), others would necessarily lead a more deprived life (that is, those with less access to global resources). Since our analysis is primarily concerned with evaluating whether a good life can be extended to all people without exceeding planetary boundaries, we have adopted an equal per capita approach to defining biophysical boundaries.

We downscale four planetary boundaries (climate change, land-system change, freshwater use and biogeochemical flows) to per capita equivalents, following the approach proposed by the Swedish Environmental Protection Agency[9]. Per capita biophysical boundaries are then compared to consumption-based footprint indicators that account for international trade. In addition, we include two further consumption-based footprint indicators (ecological footprint and material footprint), and compare these to their suggested maximum sustainable levels[5]. Since the planetary boundary for biogeochemical flows is represented by two separate indicators (nitrogen and phosphorus), seven indicators are developed in total (Table 1). (See Supplementary Information for details on the individual biophysical indicators and Supplementary Table 1 for data sources.)

Establishing social thresholds. We base our selection of social indicators on Raworth's SJS framework[1]. Raworth identified 11 social issues mentioned in at least half of the submissions to the Rio+20 conference. These collectively define the social foundation in the safe and just space.

Two previous studies have applied the SJS framework at the national/regional scale. In their framework for South Africa, Cole et al.[12] use the South African Index of Multiple Deprivation to select social goals. The result is a set of 11 goals that overlaps substantially with the set proposed by Raworth (Supplementary Table 5). The largest difference is the addition of indicators related to housing and safety, and the omission of social and gender equality indicators on the grounds that these are cross-cutting issues that should be incorporated into the other social measures. In their framework for two regions in China, Dearing et al.[13] use a smaller set of 8 social goals, which does not include indicators of equality, voice, or resilience due to a lack of data for these.

In comparison, the SDGs identify 17 goals, of which 12 could be categorized as social objectives (4 are environmental and 1 refers to the process of implementation)[21]. At a high level, these goals align quite well with the social foundation in the SJS framework, although there are some differences in the specifics proposed. The largest difference is the inclusion of goals related to sustainable cities and industry/innovation in the SDGs. The first 8 goals, however, are very consistent across the sources shown in Supplementary Table 5.

We include the first eight of the social goals in our analysis, as well as measures of equality, social support and life satisfaction (Table 2). Although we agree to some extent with the claim of Cole et al.[12] that equality is a cross-cutting issue that should be incorporated into the other social indicators, it is not easy to do this in practice. We therefore include equality as a separate indicator, as proposed in Raworth's framework[1]. We include life satisfaction (in addition to health) to provide both subjective and objective measures of well-being, and include social support due to its importance for well-being[49].

With respect to our analytic framework (Fig. 1), life satisfaction and healthy life expectancy are classified as measures of well-being (or ultimate ends), while the other nine social indicators are classified as need satisfiers (or intermediate ends). This classification is consistent with the basic needs approach[19,20], and also reflects survey results indicating that health and happiness are generally perceived to be higher-order goals. For instance, when asked "What matters most in life?" the two most frequent responses in the Gallup International Millennium Survey, which interviewed 57,000 adults in 60 different countries, were good health and a happy family life[52]. (See Supplementary Information for details on the individual social indicators and Supplementary Table 2 for data sources.)

Calculating the strength of relationships. The strength of the relationship between each biophysical and social indicator pair was estimated using ordinary least squares (OLS) regression. Three curves were tested in each case: (1) linear, (2) linear–logarithmic and (3) saturation. The equation for each curve is provided below:

$$y = a_1 + b_1 x \tag{1}$$

$$y = a_2 + b_2 \log x \tag{2}$$

$$\log(y_{\text{sat}} - y) = a_3 + b_3 \log x \tag{3}$$

where x is the biophysical indicator, y is the social indicator, a and b are the regression coefficients and y_{sat} is the saturation value of the social indicator (used for estimating saturation curves). The saturation value must be determined from the data, and following ref. [32] we have used $y_{\text{sat}} = 1.1\max(y)$. However, changing the coefficient (to something other than 1.1) does not significantly change our results.

Linear and linear–logarithmic functions are well known and commonly used in regression analysis. Saturation curves, which are an asymptotic function, have been shown to provide a very good fit for relationships between human development and environment impact[32]. We have therefore included them in our regression analysis as well.

Statistical outliers in the biophysical data were identified by plotting scatterplots of the footprint indicators against both population and GDP. Based on this method, data from the Eora MRIO database[53,54] were excluded for four countries (Belarus, Ethiopia, Sudan and Zimbabwe). Statistical outliers in the social data were considered using box plots and histograms, but no outliers were identified in the social data.

Given that we performed repeated regressions (77 variable pairs times 3 curves each = 231 tests), we used a relatively low α level of 0.01 to avoid an inflated type I error rate. To detect a moderate effect size (Cohen's $f^2 = 0.25$, $R^2 = 0.20$) with a power of 0.80 and $\alpha = 0.01$ requires a minimum N of 50, which was satisfied by all of our regressions as shown in Supplementary Table 4.

The normality of the residuals produced in each regression was tested using the Kolmogorov–Smirnov (K–S) test, and any results that did not satisfy the normality criterion were discarded. Of the remaining results, the best-fit curve was determined using Akaike's Information Criterion (AIC).

AIC is a measure of the relative quality of different statistical models, based on the maximum likelihood estimates of the parameters[55]. It trades off goodness-of-fit against the complexity of the statistical model. For OLS regression with normally distributed residuals, AIC may be calculated using the following equation:

$$\mathrm{AIC} = N\log\left(\frac{\mathrm{RSS}}{N}\right) + 2K \tag{4}$$

where N is the number of data points, RSS is the residual sum of squares and K is the number of model parameters. A better quality model is indicated by a lower value of AIC.

Importantly, the saturation curve given by equation (3) does not express y as a function of x. Rather, it expresses $\log(y_{\mathrm{sat}} - y)$ as a function of x, and thus the RSS determined from this regression is not directly comparable to the RSS determined using equations (1) and (2). Therefore, to calculate a comparable value of AIC, a revised estimate of the residual sum of squares RSS_c was calculated based on the difference between y and the curve estimated using equation (3).

The difference in the functional form of equation (3) also means that the R^2 value determined for this curve using OLS regression is not directly comparable to the R^2 values for the other two curves. The R^2 value for equation (3) expresses the variance in $\log(y_{\mathrm{sat}} - y)$ that is explained by x, rather than the variance in y that is explained by x. Therefore, a comparable estimate of the coefficient of determination was calculated based on the following equation:

$$R^2 = 1 - \frac{\mathrm{RSS}_c}{\mathrm{TSS}_c} \tag{5}$$

where RSS_c and TSS_c are the residual sum of squares and total sum of squares, respectively, calculated based on the difference between y and the curve estimated using equation (3). With this adjustment, all reported R^2 values express the variance in y that is explained by x. Given that AIC expresses the relative quality of each model (not its absolute quality or statistical significance), the comparable R^2 and p values are reported in Supplementary Table 3 as the more useful statistics.

An illustration of the method is shown in Supplementary Fig. 3 for the regressions involving CO_2 emissions. The social indicators most tightly coupled to CO_2 emissions are educational enrolment, sanitation and access to energy. For these social indicators, CO_2 emissions explain around 70% of the variation in social performance (as indicated by the comparable R^2 values). The social indicator least tightly coupled to CO_2 emissions is employment (which shows no statistically significant relationship).

Estimating resource use associated with social thresholds. To estimate the level of resource use associated with extending a good life to 7 billion people, the median value of the 20 data points closest to the social thresholds in Table 2 was calculated for each biophysical–social indicator pair. These median values were then compared to the per capita biophysical boundaries (Table 1) to evaluate the resource use implications of achieving a sufficiently high score on each social indicator. Best performance was estimated by taking the lowest level of resource use achieved by a country satisfying the social threshold in each biophysical–social indicator pair. As in the median performance analysis, the value obtained was compared to the per capita biophysical boundaries.

There are a number of different ways that the resource use associated with a given level of social performance could be estimated empirically. We explored three methods: (i) estimation using regression curves, (ii) estimation using median performance, and (iii) estimation using best performance. Each method is discussed below.

Regression curves. The first method that we explored was to use the best-fit curves identified for each biophysical–social indicator pair to estimate the level of resource use associated with a given social threshold. For example, if the best-fit curve between a given social indicator (for example, healthy life expectancy) and a given biophysical indicator (for example, CO_2 emissions) was found to be linear–logarithmic, then following equation (2), the level of resource use, x^*, associated with a given social threshold, y^*, would be specified by the following equation:

$$x^* = \exp\left(\frac{y^* - a_2}{b_2}\right) \tag{6}$$

where a_2 and b_2 are the coefficients of the regression. This method tended to generate quite high values of x^* for linear–logarithmic and saturation curves, and displayed a high degree of sensitivity to the choice of y^* for these curves, given that the curves are generally relatively flat around the y^* value. (Thus a small change in y^* leads to a large change in x^* with this method.)

Median performance. The second method that we explored was to calculate the mean or median x value for the n data points closest to y^* (including points both above and below y^*). The regression analysis revealed that the best-fit curve for the biophysical and social indicator pairs was generally a linear–logarithmic or saturation curve, and thus the median was a more appropriate measure to use than the mean (which would be more appropriate if the relationship were linear). We chose a value of $n = 20$ to include a representative subset of the points closest to the social threshold. The median performance method generated lower x^* values than the regression curve approach overall, and was less sensitive to changes in the choice of y^*.

Best performance. The final method that we explored was to identify the minimum x value corresponding to $y \geq y^*$. This approach yielded the lowest x^* values of the three methods. For each biophysical–social indicator pair, the x^* value calculated using this method represents the lowest level of resource use at which a sufficient social outcome is achieved within current country data. The main risk with this method, however, is that the best-performing country may be anomalous, and thus the results may exaggerate what can be achieved in other countries.

A hybrid approach. Although we concluded that regression analysis is a very good way to estimate the strength and shape of the relationships between biophysical and social indicators, it is a weaker approach for estimating the level of resource use associated with a given social threshold (due to the high degree of sensitivity to changes in y^*). Therefore, we applied the median performance method to estimate the level of resource use associated with a given social threshold, and complemented this approach with the analysis of best performers.

While our analysis treats each of the biophysical and social indicators as independent pairs, in reality the indicators may be coupled and move together. Reducing CO_2 emissions would (by definition) reduce ecological footprint, while improving health would likely increase life satisfaction. The interdependency of variables is acknowledged in the planetary boundaries framework[3], and within our own analytic framework.

Data availability. Our analysis relies on data from multiple sources, the main ones being the Eora MRIO database[53,54] for the biophysical indicators, and the World Bank[56] and *World Happiness Report*[49] for the social indicators (see Supplementary Tables 1 and 2 for all sources). Unless otherwise noted in the Supplementary Information, all data are for the year 2011, which is the most recent year for which most indicators were available. It is also the year that world population reached 7 billion people, which is the number used to calculate per capita biophysical boundaries. The countries considered in our analysis are restricted to those with a population of at least 1 million people. See Supplementary Data for country-level data for the 7 biophysical and 11 social indicators. The data are also available via an interactive website (https://goodlife.leeds.ac.uk), which allows users to query the dataset, generate visualizations and produce 'safe and just space' plots similar to Fig. 3 for all countries.

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Author contributions

D.W.O. designed the study. D.W.O., A.L.F, W.F.L. and J.K.S. assembled the data, performed the analysis and wrote the manuscript.

Competing interests

The authors declare no competing financial interests.

Additional information

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