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LETTER

Connecting global emissions to fundamental human needs and their satisfaction

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Abstract

While quality of life (QOL) is the result of satisfying human needs, our current provision strategies result in global environmental degradation. To ensure sustainable QOL, we need to understand the environmental impact of human needs satisfaction. In this paper we deconstruct QOL, and apply the fundamental human needs framework developed by Max-Neef *et al* to calculate the carbon and energy footprints of *subsistence*, *protection*, *creation*, *freedom*, *leisure*, *identity*, *understanding* and *participation*. We find that half of global carbon emissions are driven by *subsistence* and *protection*. A similar amount are due to *freedom*, *identity*, *creation* and *leisure* together, whereas *understanding* and *participation* jointly account for less than 4% of global emissions. We use 35 objective and subjective indicators to evaluate human needs satisfaction and their associated carbon footprints across nations. We find that the relationship between QOL and environmental impact is more complex than previously identified through aggregated or single indicators. Satisfying needs such as *protection*, *identity* and *leisure* is generally not correlated with their corresponding footprints. In contrast, the likelihood of satisfying needs for *understanding*, *creation*, *participation* and *freedom*, increases steeply when moving from low to moderate emissions, and then stagnates. Most objective indicators show a threshold trend with respect to footprints, but most subjective indicators show no relationship, except for *freedom* and *creation*. Our study signals the importance of considering both subjective and objective satisfaction to assess QOL-impact relationships at the needs level. In this way, resources could be strategically invested where they strongly relate to social outcomes, and spared where non-consumption satisfiers could be more effective. Through this approach, decoupling human needs satisfaction from environmental damage becomes more attainable.

Introduction

Sustainable development and quality of life (QOL) share a focus on human needs. Sustainable development is defined as satisfying human needs without compromising natural and social capital [1] while QOL is a result of satisfied physical, psychological, and social needs [2–4]. Needs can be satisfied by immaterial means [2, 4], such as good health or social relations [4], or material ones, such as economic goods and infrastructures [4–6]. The status-quo is to pursue high QOL through rampant consumption [7], which invariably leads to environmental damage [9, 10] but does not necessarily satisfies needs [11–13]. A step towards more sustainable strategies for enhanced QOL is to clarify the interaction between needs satisfaction, consumption, and environmental impact [2, 5, 11, 14].

Development theories

Different theories of environmental sociology propose relationships between economic growth, environmental degradation and QOL. Modernization theories, including 'economic and ecological modernization', argue for the positive role of economic growth and consumption in achieving sustainability and improving QOL

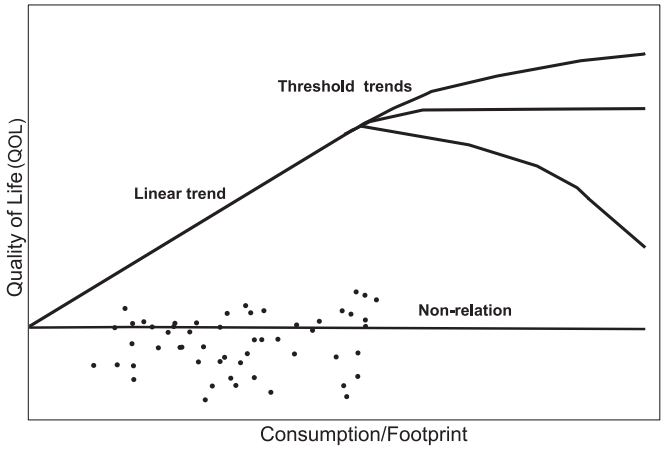

Figure 1. Proposed trends between consumption and quality of life in relation to development theories [2, 4, 5, 7, 11, 12, 19, 21, 22]. N.B.: In this paper, footprints are a direct function of consumption [9, 23] (see Methods).

[12, 15, 16]. These theories rely on assumptions of neoclassical economics and thus predict a strong link between consumption and QOL, represented by the linear positive relationship shown in figure 1.

In contrast, the 'treadmills of production' theory states that, due to its expansive nature, economic growth is in fundamental conflict with environmental protection [12, 16]. This theory predicts that modern nations reach a point of 'decreased social efficiency of natural resource utilization', where initial steep increases in QOL might correlate with increasing carbon footprint but reach a threshold of diminishing returns and eventually a steady state [17] (figure 1). After this threshold, each consumption unit generates more environmental damage and less welfare than it did at lower levels of development [12]. In some cases, QOL can even decline when increased consumption results in more harm than benefit [2, 12].

The theory of 'human ecology' considers a broader context, recognizing that QOL might also be affected by non-consumption factors [16] such as social dyanmics [18], relationships [19], health [3], climate conditions [12, 16], political factors [5, 16], etc (see [12, 16, 20]). In this case, changes in consumption do not necessarily predict changes in well-being, as shown by the 'non-relation' constant or scatter plots in figure 1. The supplementary information (SI1 is available online at stacks.iop.org/ERL/14/014002/mmedia) presents a summary of the trends and related concepts from other disciplines that link consumption and non-consumption to QOL.

Empirical evidence: QOL and consumption

Empirical findings of threshold and weak relations between QOL and consumption point to the opportunity of reducing impact without affecting the QOL in wealthy nations [7, 24–26]. Early evidence for the threshold pattern was demonstrated by the Easterlin Paradox [27], where consumption positively correlates with QOL but only up to a point and not over the long term [27, 28]. Further investigations argued for a trend of diminishing returns between QOL and consumption [29–31]. Nevertheless, both down-concave trends concede that additional consumption yields steeper benefits to the QOL of the poor, compared to the rich [19, 31]. Although studies confirm the Easterlin Paradox at different geographical scopes [12, 24, 32], they generally overlook using subjective life satisfaction as an adequate proxy for needs satisfaction [31, 33], and of using economic proxies for resource use (SI1 and SI5).

Empirical evidence: QOL and environmental impact

Sustainability-oriented studies further confirm threshold relationships between objective indicators of QOL, energy use [14, 25, 26, 34–36] or carbon footprint [12, 13, 24, 37–41]. The marginal benefit of additional CO_2 emissions, as measured by increased QOL, quickly decreases at a carbon footprint of around 3 tons CO_2 per capita (t CO_2/cap) [13, 37] and becomes indistinguishable from zero at values above 10 t CO_2/cap [13, 34, 37]. A QOL-CO_2 threshold has been reported for several indicators of QOL, including life expectancy [34, 37, 38, 41], infrastructure access [13, 35, 36], education [5, 24, 26] and the Index of Sustainable Economic Welfare [17, 42]. These findings signal opportunities for resource efficient development by directing resources to areas that have demonstrable social benefits [5, 8], such as child-rearing [4, 17], education [24, 43], access to energy [35], nutrition [13, 39] and sanitation [13]. However, most measures of environmental impact have been limited to national footprints [24, 37, 41] or consumption domains [9, 10].

Policymakers and the general public are eager for measures of progress in terms of societal outcomes rather than monetary inputs (e.g. healthy people rather than investments in the health sector) [5]. A multidimensional approach to the QOL-impact relationship considers the underlying human needs that enhance QOL [8] and whose satisfaction ultimately

drives impact [14]. Apart from few exceptions [24], most studies measure QOL through single, composite, or broad indicators, such as life expectancy [36–38, 41], human development index [34], or life satisfaction [12, 27–30, 32], respectively. However, QOL not only depends on the level to which human needs are objectively met, but also on peoples' subjective satisfaction with respect to such levels [3, 8]. Initiatives such as the Better Life Index [44] or the Social Progress Index [45] demonstrate the complementarity of objective and subjective indicators for sounder policies [8].

Assessing environmental impact and satisfaction of fundamental human needs

We apply the framework of fundamental human needs to study the link between sustainability and QOL [2]. Max-Neef and colleagues recognized the bias of studying consumption and QOL based on consumption domains (e.g. transport, housing) [9, 23] rather than looking at their contribution to life domains (e.g. work, leisure, health) [3]. They proposed that all that we have and do, as well as the spaces in which we interact and the skills we build, are potential 'satisfiers' that contribute to QOL. In their view, QOL is a consequence of satisfying nine fundamental human needs: *subsistence*, *protection, creation*, *identity*, *affection*, *participation*, *understanding*, *leisure* and *freedom* [2]. These human needs are immutable across societies and throughout time. While other frameworks define universal saisfiers [46], Max-Neef argues that strategies to satisfy needs are entirely flexible and determined by each individual or group. Thus, satisfiers can be sustainable or unsustainable, based on different types of capital: natural, social and cultural [47].

We find this framework useful as it encompasses all the QOL-consumption relations described in figure 1 [2]. Further, the concept of satisfiers for needs is comprehensive, and inclusive of market and non-market goods. In contrast to similar frameworks [48], Max-Neef provides abundant examples that can be used as guidelines to model goods as satisfiers and to choose indicators of need satisfaction (SI table 3) [49]. Unlike the hierarchical taxonomy of Maslow [50], Max-Neef proposes a horizontal view of needs which is supported by robust research that reports needs to be fairly independent of each other [19]. For example, individuals with low material living standards can have better psychological and social well-being than their well-off counterparts [18, 19, 32, 51].

We take a multi-dimensional approach to QOL [3, 8] by applying the framework of fundamental human needs. As others before us, we model economic goods as satisfiers [47, 52] as a basis to estimate the energy and carbon footprints of fundamental human needs at a global and country level [53]. We then perform a cross-sectional analysis of 35 different objective and subjective indicators of needs satisfaction as a function of their footprints across 44 nations. To our knowledge, this is the first study to provide global and country-level estimates of the carbon and energy associated with fundamental human needs and their satisfaction.

Methods

This study linked final consumption of market goods and services to the needs that they allegedly satisfy. This made it possible to calculate consumption and associated energy and carbon footprints for each human need at the country level. We then assessed needs satisfaction across nations and examined the relationship when plotted against each need's carbon footprint. All footprints calculations and most QOL indicators are for the year 2007, unless otherwise specified in the SI (appendix).

Linking economic goods to human needs

First, we proposed a correspondence between the 200 economic goods available in the input–output database (EXIOBASE3-2007 [54, 55]) and the nine human needs [2] as shown in step 1 of table 1. Through group discussions, we discarded the most unlikely relationships between market goods and needs following Max-Neef's taxonomy and examples as guidelines [2, 49]. In the development of the correspondence matrix, we established conceptual identities between goods and needs to use as a guiding logic [2, 49] (see SI2 for details). As a result, *subsistence* relied heavily on food and housing, and to a lesser extent on transport and manufactured goods. *Protection* included health care, safety and financial security and can be satisfied by a range of goods, from insurances to heating fuels. *Creation* included the means to create and exercise creativity in both formal and informal work, as well as the application of art and crafts skills to material objects [56]. *Freedom*, understood as spatial and temporal plasticity, relied on market items that save time such as transport, domestic appliances and services (e.g. outsourcing of household work). *Leisure* included transport and energy for pleasure, as well as recreational services and entertainment. *Identity* relates mostly to goods that enable expression of preferences such as luxury items, clothing or diets. *Participation* related to communication devices, media and club memberships, while *understanding* associated to diverse pedagogic goods, from computers to educational services. *Affection* was not linked to any market good in the database and is therefore not included in this analysis.

A novelty of our model is to allow one market good to satisfy several needs simultaneously as 'synergistic satisfiers' [49]. For example, purchasing food directly satisfies *subsistence* but also *identity*, as reflected in diet and cuisine. We recognized that *subsistence* and *protection* are more directly reliant on material prerequisites compared to other needs (*participation*, *identity*, etc)

Table 1. Steps 1 and 2 establish a correspondence matrix between economic goods and fundamental needs. Step 3 characterizes the uncertainty in step 2. This procedure was conducted for 200 economic goods. Su: Subsistence, Pr: Protection, Af: Affection, Un: Understanding, Pa: Participation, Le: Leisure, Cr: Creation, Id: Identity, Fr: Freedom. Full concordance matrix available in the supplementary data.

Step 1. Concordance	Su.	Pr.	Af.	Un.	Pa.	Le.	Cr.	Id.	Fr.	
Clothing	1	0	0	0	0	0	0	1	0	Focus group to establish a match between products and needs by discarding relationships (0s) according to Max-Neef's examples
Waste management	1	1	0	0	0	0	0	0	0	
Step 2. Allocation										
Clothing	0.2	0	0	0	0	0	0	0.8	0	Allocation ratios for synergistic goods according to the expenditure ratio between higher/lower quintiles for each good type (US survey)
Waste management	0.5	0.5	0	0	0	0	0	0	0	
Step 3. Uncertainty test										
Clothing	X	0	0	0	0	0	0	X	0	Characterize the uncertainty of using US data by running a Monte Carlo simulation to test all possible splits in X
Waste management	X	X	0	0	0	0	0	0	0	

Table 2. Indicators by type and data sources. Thirty-five indicators were compiled to use as proxy for human need satisfaction. When different data sources had identical questions, we combined them to prevent missing data points. All indicators report 2007 data unless otherwise specified in the SI appendix.

Type of indicator	Data sources
Objective indicators	
Child survival rate, democracy index, non-obese adults, long term employment, inverse homicide rate, inverse fertility rate, access to sanitation, access to modern fuels, access to electricity, global creativity index, institutional freedom, income equality, residual free time, increased knowledge, education index, reading comprehension	Social progress index [45] World bank indicators [64] Central intelligence agency [65] World health organization [66] Global democracy ranking [67] The global creativity index [68] OECD labour force and time use [69, 70] Programme for International Student Assessment (PISA) [71]
Subjective indicators (satisfaction and values)	
Subjective health, standard of living, health care quality, feeling safe, satisfaction with labor market, affordable housing, satisfaction with creativity, freedom to choose, authenticity, leisure satisfaction, importance of leisure, importance of freedom, importance of creativity, self-expression, learn new things in life, satisfaction with democracy, importance of democracy, overall life satisfaction	Human Development Report :UNDP [62] World Value Survey [72] European Social Survey [73] International Social Survey [74]

[7, 24, 40]. Accordingly, we derived an allocation key based on the expenditure ratios between the lowest and highest income groups for each type of market good [40] by assuming that discretionary expenditure in synergistic basic goods aims to satisfy non-physical needs [40]. For example, if people in the lowest income quintiles spent on average 30 USD per capita on clothing, while the highest income quintiles spent 100 USD/cap, we allocated 30% of the total expenditure on clothing as a satisfier for *subsistence* whilst the remaining 70% went to *identity*. We used a US expenditure survey [57] to derive ratios and split synergistic satisfiers between basic needs (*subsistence* and *protection*) and other needs (step 2 table 1).

Finally, we conducted a Monte Carlo simulation to characterize the uncertainty of generalizing the allocation ratios from step 2 to the global economy. By testing all possible splits, we find the same relative hierarchy of the needs' carbon footprints and our estimates fall within the interquartile range of dispersion (see SI2). While the allocation values can certainly be refined by using country-specific data, our initial estimate proved to be robust and generalizable.

Consumption-based footprints

Consumption footprints consider all the energy and carbon emissions embodied in the production of goods, and attribute them to final consumers. In this sense, the carbon footprint of a nation equals the direct emissions occurring due to households' transport, heating and cooking, plus the embodied impact in the production of all consumed goods and services [53]. We model the final demand of households, governments, and non-profit institutions serving households for the year 2007, assuming that they all consume to satisfy societal needs.

We used the standard Leontief Input–Output model [58] to calculate energy and carbon footprints for 2007 based in EXIOBASE3, an open-access environmentally extended multiregional input–output database [55, 59] that captures the global economic activity and resources. We consider both combustion and non-combustion greenhouse gases (CO_2, CH_4, N_2O and SF_6) [55] normalized to carbon dioxide equivalents (CO_2eq) by using the IPCC 2007 characterization factors [55]. The net energy footprint includes the primary and secondary energy carriers used by industries for production of goods [55, 60]. Details about the footprints calculations are found in the SI3 [55, 60]. EXIOBASE3 covers the 44 largest economies, which make up 91% of global GDP and 65% of the world population. The rest of the world is represented by five regions of Middle East, America, Europe, Asia Pacific and Africa [55]. The global carbon and net energy embodied in consumption are used for the first section of results i.e. including the Rest of the World regions (figure 2). Embodied plus direct household energy and emissions were considered to compute footprints of needs across the 44 individual countries and assess need satisfaction (figures 3 and 4 and table 4). Finally, by applying the concept of consumption and footprint elasticity [9, 23], we compared marginal differences in consumption and footprints with respect to differences in the total consumption associated to needs (see SI3).

Assessing need satisfaction and QOL-footprint trends

Table 2 presents our dashboard of indicators, compiled under the following heuristics [8]: (1) QOL is multi-dimensional and should be measured in terms of specific human needs; (2) the evaluation of multiple needs should combine different scales: from individuals to societal level; (3) combining subjective and objective

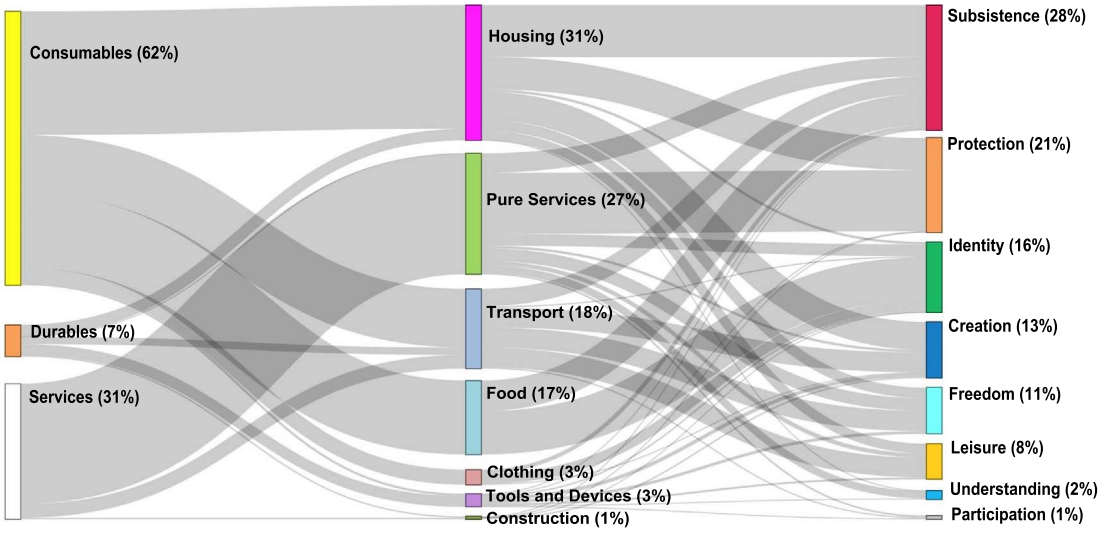

Figure 2. The global carbon footprint embodied in human needs under different classifications of goods. Results represent global final consumption by households, governments and non-profit serving households in 2007. The global carbon emissions embodied in consumption for 2007 amounts to 28 Gt CO_2 eq. The figure displays the links between three different aggregations of the 200 market goods in EXIOBASE3 by type of consumer good, classified as durable goods, non-durable goods and services (left), by consumption category or functionality (middle) [23] and by human needs they satisfy [49] (right). The equivalent figure for global energy footprint is available in the SI (figure 2). NB: The Sankey diagrams only reflect embodied emissions, additional 5 Gt CO_2 eq make up direct household emissions which are considered for the rest of the results.

measures is necessary to identify the inputs that improve QOL. To guide our selection of indicators, we referred to Max-Neef's examples of satisfiers for the existential categories of 'being' and 'doing' [2, 49]. Detailed considerations and rationale for indicator choice are found in the supplementary material (see SI3 and SI table 1).

Subjective well-being indicators are self-reports that capture the percentage of individuals who are satisfied with respect to a need. When available, we included measures of values to represent the importance of a certain need for a population [61]. Objective indicators are assessed by a third party and used to represent infrastructure, social institutions, or health status [5, 8]. For example, to assess the subjective satisfaction of *freedom* we used the question: 'are you satisfied with freedom to choose what to do with your life?' [62]. To assess the importance of freedom, we used the Schwarz scale item: 'it is important to take own decisions. She/he likes to be free and not depend on others' [63]. To measure the objective status of freedom in a country, we took the measure of tolerance, inclusion, and personal rights reported in the Social Progress Index [45]. We compiled 35 objective and subjective country-level indicators from the databases (in table 2). When sensible, we prioritized single over composite indicators to prevent conceptual overlaps. However, objective indicators for freedom, democracy, and creativity do cover multiple dimensions. See the SI for the full referenced inventory of indicators for each need and the measure of satisfaction rates (appendix).

Using 'need satisfaction rate' as the dependent variable and the 'per capita carbon footprint of need' as the independent variable, we ran unweighted cross-country bivariate regressions to test the association between carbon footprint of needs and satisfaction outcomes (see SI 5). The mathematical forms of the models are, respectively:

$$Y_{ji} = \beta_o + \beta_1 CF_{ni} + \upsilon_{ni} \quad (1)$$

$$Y_{ji} = \beta_o + \beta_1 CF_{ni} + \beta_2 CF_{ni}^2 + \upsilon_{ni} \quad (2)$$

$$Y_{ji} = \beta_o CF_{ni}^{\beta_1} + \upsilon_{ni}, \quad (3)$$

where Y is the reported satisfaction rate for each indicator j of each need i. CF is the per capita carbon footprint of each need i, in every nation n. The β coefficients are constants that result from the fit and υ is the error term. The cut-off criteria to accept a model fit between carbon footprint and need satisfaction is an adjusted R^2 above 0.28, while the criteria to accept a statistical significant relationship is set at 5% (p-value <0.05) for all the relationships investigated: linear, quadratic and power law. In similar studies, objective indicators often yield an R^2 above 0.5, while for subjective or social indicators, values lower than 0.25 are commonly accepted, given statistical significance [13, 24, 75]. Because we combine an assortment of indicator types and given our sample size ($40 < N < 50$), we establish our criteria seeking to discard weak evidence.

We hypothesize that linear curve fits support the aforementioned theory of 'ecological modernization' while nonlinear fits sustain the 'treadmills of production' theory. A significant power-law fit would imply

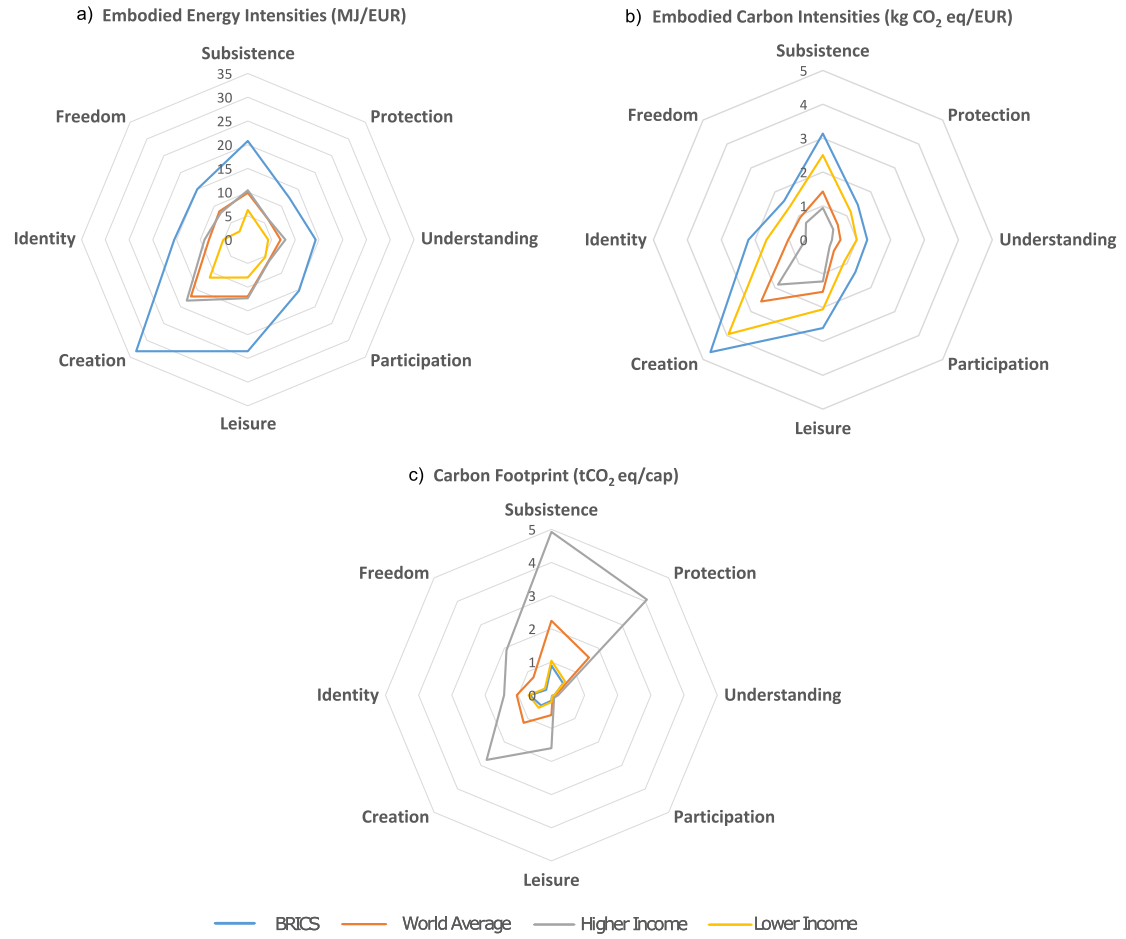

Figure 3. Average energy (a) and carbon (b) intensities and carbon footprint (c) of needs for different groups of nations in 2007. Higher income (gray line) groups the 21 wealthiest nations (866 million people). Lower income (yellow line) groups the 22 less wealthy nations (3.4 billion people), of which 2.8 billion live in Brazil, Russia, India, China and South Africa (BRICS, blue line). World Average includes Rest of the World regions (Africa, Europe, America, Asia and Pacific). Groups of nations, footprint values and economic data are available in the supplementary material.

diminishing returns on QOL. Quadratic fits might indicate saturating thresholds or even declining QOL, given a negative significant coefficient. Non-relationships might be explained by factors of human ecology [12]. However, we do not account explicitly for such factors and thus cannot confirm nor discard their role.

Results

Carbon footprints of human needs

At a global level, *subsistence* drives 28% of global emissions followed by *protection, freedom, identity,* and *creation* (figure 2). While food is important, housing contributes the largest share of the carbon footprint of *subsistence*. *Protection* has the second highest carbon footprint with 21% of global emissions and the highest expenditure (see SI), in line with previous findings which trace 50% of impact to *subsistence* and *protection* [52]. *Freedom* and *identity* together make up around 27% of global emissions. *Creation* and *leisure* underlie around 21% of the total carbon emissions, while *understanding* and *participation* amount about 3% of the total carbon footprint. Figure 2 presents the linkages between human needs and the common categorization of goods by consumption domains (housing, services, mobility, etc). The supplementary data contains the expenditure and footprints of human needs for the 44 nations and 5 world regions.

Marginal changes and environmental intensity of needs

Creation is the most intensive need with a world average of 2.2 kg CO_2 eq and 36 MJ per EUR of expenditure, followed by *subsistence* and *leisure* (figures 3(a), (b)). By contrast, *understanding* and *protection* are the least intensive, due to the large share of services that they require [9] (figure 2). The 22 poorest nations of our sample expend 2–4 times more carbon and energy per unit of consumption, compared to the 22 wealthiest (figures 3(a), (b)). However, the low intensity of wealthy nations is counteracted by their consumption volume, resulting in 2–7 times

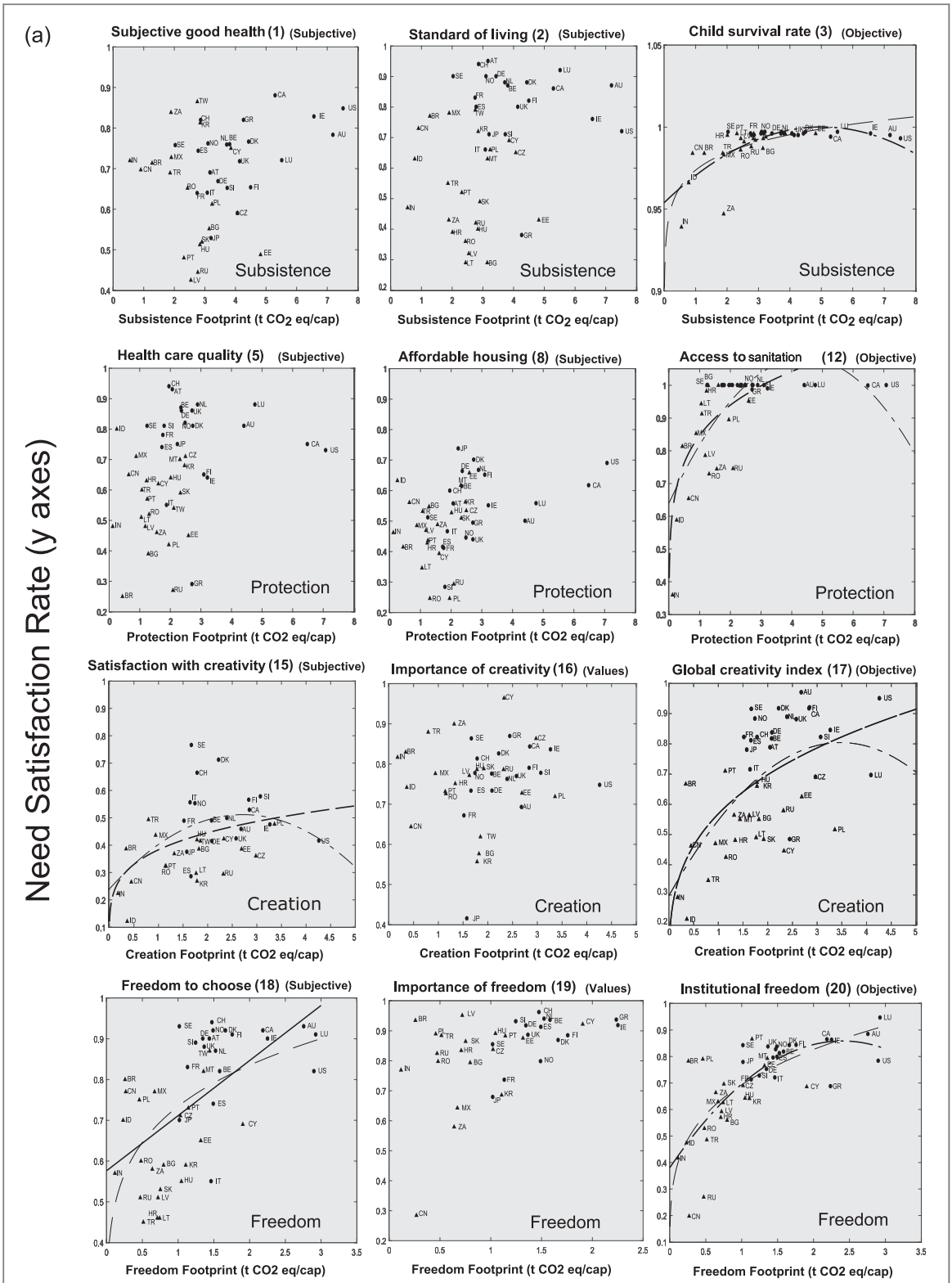

Figure 4. (a), (b) Plots of need satisfaction expressed in percentage (*y* axes) against carbon footprint of needs (*x* axes) for each country in 2007. The two best fitting models ($R^2 > 0.28$) appear on the plot represented by linear (—), quadratic (- — -) and power law (— —) and the best fit is bolded. Key: 'Freedom to choose' fits a linear trend while 'Importance of freedom' is scattered and 'Institutional Freedom' fits a curvilinear trend. ● = higher income nations ▲ = lower income nations. N.B. The additional plots for Subsistence, Protection, Understanding and 'general' well-being are available in the SI.

higher footprints, compared to the poorest nations, e.g. twice the carbon footprint for *understanding*, 4 times higher for *subsistence* and up to 7 times higher for *protection* and *leisure* (figure 3(c)). These trends point to the role of economic development in lowering the carbon intensity of human needs [9, 10]. However, it also signals that the benefits of more efficient technical systems and lower intensities are undermined by exacerbated consumption via the rebound effect [76, 77].

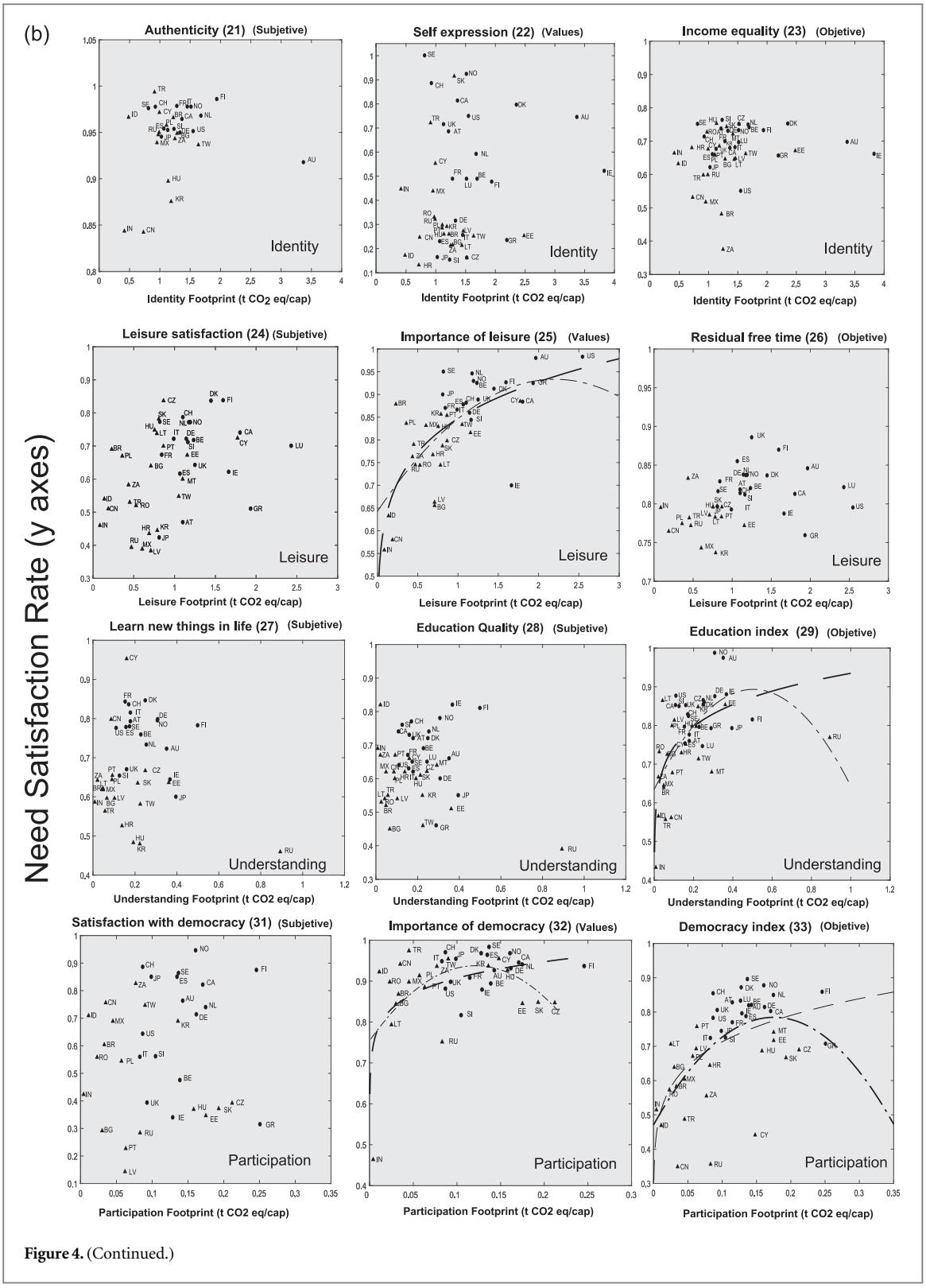

Figure 4. (Continued.)

Brazil, Russia, India, China and South Africa (BRICS) have the lowest footprints per capita, but the highest impact intensities. Since 2.8 billon people inhabit the emergent economies of the BRICS group, the current footprint differences between wealthy nations and the BRICS (figure 3(c)) signals the potential for increased emissions in the coming decades. It is worth noting that all groups of nations show a similar distribution of carbon among needs, and only the magnitudes vary (figure 3(c)). Interestingly, this is not the case when looking at consumption categories (figure 2), where low-income nations tend to concentrate emissions in food and housing [9, 23].

We used elasticities to test the sensitivity of changes in consumption and footprints of needs with respect to changes in total expenditure (table 3). A 1% increases in total consumption corresponds to more than 1% increases in the consumption of most needs

Table 3. Elasticities (ε) of needs indicate the percent change in the indicator (footprints or consumption) for each need with respect to a 1% increase in total consumption. All reported coefficients are significant to an alpha of 1%. ε is the $\beta 1$ slope resulting from running cross-sectional log-log regressions. The dependent variables are per capita consumption and footprints for each need and the independent variable is total per capita expenditure for the sample of 44 nations.

	Consumption		Carbon footprint		Energy footprint	
	ε	R^2	ε	R^2	ε	R^2
Subsistence	0.99	0.99	0.49	0.75	0.43	0.77
Protection	1.09	0.97	0.60	0.70	0.47	0.76
Freedom	0.98	0.97	0.65	0.85	0.45	0.81
Identity	0.87	0.96	0.35	0.55	0.29	0.41
Creation	1.01	0.97	0.57	0.69	0.45	0.72
Leisure	1.01	0.98	0.68	0.84	0.46	0.79
Participation	1.10	0.93	0.68	0.69	0.57	0.62
Understanding	1.09	0.91	0.67	0.55	0.51	0.46

($\varepsilon > 1$), except for *subsistence*, *identity* and *freedom*, which change at decreasing rates ($\varepsilon < 1$). Carbon and energy footprints both change at decreasing rates with respect to expenditure. However, the carbon footprint of needs is generally more sensitive to consumption changes [9]. *Protection*, *leisure*, *participation* and *understanding* are some of the most sensitive needs, as shown by a higher ε coefficient. On the contrary, *identity* is one of the least sensitive, as it is satisfied by a large share of food products (figure 2), which are basic goods [10].

Carbon emissions and need satisfaction

When assessing needs satisfaction, we observe no universal pattern between the degree of satisfaction and the carbon emissions expended in those needs (figures 4(a), (b)). The threshold pattern found in previous studies [13, 24, 27, 28, 34, 36, 37] is confirmed for 5 indicators; 11 of which are objective, 2 value indicators and 2 subjective well-being. For 20 out of 35 relationships investigated, we find no correlation between the carbon footprint of human needs and their satisfaction. The diversity of relationships becomes evident when exploring figures 4(a), (b). Table 4 summarizes the model fits for all 35 tested relationships. The adjusted R^2 indicates how well the carbon footprint predicts needs satisfaction i.e. the strength of the relationship (see the SI for full statistics). Regression coefficients greater than zero imply that likelihood of satisfaction increases with footprints. Negative coefficients indicate a negative correlation between satisfaction and footprints.

Subsistence

Subsistence is the need with the largest carbon footprint (figures 2 and 3(c)). The childhood survival and inverse fertility rates increase steeply at low emissions and stagnate around 2 t CO_2eq/cap, which is about 1 ton above the threshold reported for life expectancy [37]. The subjective satisfaction with health and living standards is not correlated to *subsistence* footprint.

Protection

Due to its multi-dimensional nature, we measure *protection* with ten indicators. While *protection* has the second largest footprint, seven out of ten indicators are not correlated to the footprint of *protection*. Health care quality, feeling safe, satisfaction with labor market, affordable housing, non-obese adults, long-term employment and the probability of not being murdered (inverse homicide rate) are all measures of *protection* that seem unrelated to carbon emissions as show in table 4 (Indicators 5–11). Nonetheless, the infrastructure dimensions of *protection*, such as access to modern fuels, electricity and sanitation improve rapidly and are nearly fully satisfied at a *protection* footprint of 3 t CO_2eq/cap [13, 24, 3536]. The curvilinear shape of energy and sanitation plots is driven by few emerging countries with lagging infrastructures [13, 35]. European countries such as Spain, Italy, Portugal and France, with a *protection* footprint below 2 t CO_2eq/cap, manage to provide virtually 100% of access to modern fuels and sanitation. See the SI for the plots of the *protection* indicators not shown in figure 4.

Identity

None of the indicators of *identity* satisfaction trend with emissions. The satisfaction with respect to individual authenticity proves to be universal and independent of consumption, with a satisfaction above 90% across nations. Most nations in our sample report an income equality of 60%–80% and thus equality does not vary with footprint [24]. Self-expression values represent environmental awareness, tolerance and social engagement. Countries with low self-expression are more loaded with survival values, which prioritize security, conformity and low levels of trust and tolerance [61]. We find that self-expression differs widely for countries with similar *identity* footprint (e.g. see Mexico and Sweden). Ingelhart and Welzel recognize that collective values may be heavily influenced by factors of human ecology such as cultural practices and political history, rather than consumption [61].

Creation

Subjective satisfaction with creativity at the workplace and objective measures of creativity (global creativity index) are both steeply correlated with *creation* footprints up to a threshold of around 2 t CO_2/cap. *Creation* satisfaction has been previously associated to opportunities for skilled and gainful work in high income nations [3, 56], rather than to the consumption of goods associated to *creation*, many of which are defensive goods, which aim to protect current QOL but not necessarily enhance it e.g. driving to work [5], household work (SI table 2). The importance of

Table 4. Tested relationships between needs satisfaction and carbon footprint of needs. Strong relationships are highlighted in gray. The 'trend shape' column describes the visual trend of the data plot (figure 1). The 'best fit' was selected among power law (pl), quadratic (qu) and linear (lin) fits when the adjusted coefficient of determination (R^2) is above 0.28. The second best fit is provided in 'Alt-fit' column and the relationship is validated with energy footprint. The slopes report unstandardized coefficients and the symbols *, ** and *** denote significance levels, α, of 10%, 5% and 1%, respectively.

				Carbon footprint								Energy footprint (Validation)
Human need	Type	Indicators	Trend shape	Best fit	*B* coeff	Adj. R^2	Alt-fit	*B* coeff	Adj. R^2	Best fit	*B* coeff	Adj. R^2
Subsistence	Subjective	Good health (1)	Non-relation	Quadratic	−5.50	0.09				qu	−0.5	0.10
	Subjective	Standard of living (2)	Non-relation	Linear	4.1^{**}	0.07				lin	0.6^{***}	0.19
	Objective	**Inverse Fertility Rate (3)**	**Threshold**	**Quadratic**	**1.8^{***}**	**0.51**	**pl**	**1.6^{***}**	**0.47**	**qu**	**0.2^{***}**	**0.53**
	Objective	**Child survival rate (4)**	**Threshold**	**Quadratic**	**13.5^{***}**	**0.40**	**pl**	**12.2^{***}**	**0.20**	**qu**	**1.3^{***}**	**0.44**
Protection	Subjective	Health care quality (5)	Non-relation	Quadratic	10.3^{*}	0.09				qu	1.1^{***}	0.18
	Subjective	Feeling safe (6)	Non-relation	Linear	2.6^{*}	0.05				lin	0.3^{**}	0.11
	Subjective	Satisfaction with labour market (7)	Non-relation	power	−12.50	0.00				pl	−16.2	0.01
	Subjective	Affordable housing (8)	Non-relation	Linear	3.4^{**}	0.13				lin	0.3^{***}	0.16
	Objective	Non-obese adults (9)	Non-relation	Power	-5.4^{***}	0.18				pl	-4.4^{**}	0.11
	Objective	Long-term employment (10)	Non-relation	Linear	0.60	0.03				lin	0.1^{**}	0.07
	Objective	Inverse homicide rate (11)	Non-relation	Quadratic	4.6^{**}	0.06				qu	0.3^{**}	0.06
	Objective	**Access to sanitation (12)**	**Threshold**	**Power**	**20.3^{***}**	**0.62**	**qu**	**20^{***}**	**0.50**	**pl**	**20.7^{***}**	**0.60**
	Objective	**Access to modern fuels (13)**	**Threshold**	**Power**	**17.7^{***}**	**0.54**	**qu**	**16.3^{***}**	**0.42**	**pl**	**17.7^{***}**	**0.51**
	Objective	**Access to electricity (14)**	**Threshold**	**Power**	**3.9^{***}**	**0.29**	**qu**	**4.1^{***}**	**0.14**	**pl**	**3.7^{***}**	**0.25**
Creation	**Subjective**	**Satisfaction with creativity (15)**	**Threshold**	**Power**	**27.8^{***}**	**0.29**	**qu**	**19.4^{**}**	**0.19**	**qu**	**32.8^{***}**	**0.34**
	Values	Importance of creativity (16)	Non-relation	Linear	1.10	−0.02				lin	0.1	−0.01
	Objective	**Global creativity index (17)**	**Threshold**	**Power**	**33.2^{***}**	**0.40**	**qu**	**29.2^{***}**	**0.33**	**pl**	**40.6^{***}**	**0.51**
Freedom	**Subjective**	**Freedom to choose (18)**	**Linear/Threshold**	**Linear**	**13.5^{***}**	**0.33**	**qu**	**22.4^{**}**	**0.33**	**lin**	**1.4^{***}**	**0.41**
	Values	Importance of freedom (19)	Non-relation	Linear	11.2^{***}	0.18				pl	14.4^{**}	0.16
	Objective	**Institutional freedom (20)**	**Threshold**	**Quadratic**	**39.8^{***}**	**0.54**	**pl**	**29.8^{***}**	**0.47**	**qu**	**3.4^{***}**	**0.56**
Identity	Subjective	Authenticity (21)	Non-relation	Quadratic	10.9^{**}	0.14				pl	2.9^{**}	0.15
	Values	Self-expression (22)	Non-relation	Power	26.70	0.01				pl	28.9^{*}	0.05
	Objective	Income equality (23)	Non-relation	Power	6.00	0.01				lin	0.5^{***}	0.14
Leisure	Subjective	Leisure satisfaction (24)	Non-relation	Quadratic	27.7^{**}	0.17				lin	1.3^{***}	0.28
	Values	**Importance of leisure (25)**	**Threshold**	**Power**	**13.8^{***}**	**0.53**	**qu**	**26.4^{***}**	**0.46**	**pl**	**16^{***}**	**0.59**
	Objective	Residual free time (26)	Non-relation	Quadratic	8.1^{**}	0.16				lin	0.3^{***}	0.24
Understanding	Subjective	Learn new things in life (27)	Non-relation	Quadratic	61.6^{**}	0.12				qu	4.1^{*}	0.02
	Subjective	Education Quality (28)	Non-relation	Quadratic	36.90	0.08				lin	0.3	−0.02
	Objective	**Education Index (29)**	**Threshold**	**Power**	**11.4^{***}**	**0.45**	**qu**	**102.6^{***}**	**0.38**	**pl**	**11.8^{***}**	**0.55**
	Objective	**Reading comprehension (30)**	**Threshold**	**Quadratic**	**63.4^{***}**	**0.28**	**pl**	**5.2^{***}**	**0.23**	**pl**	**5.5^{***}**	**0.28**
Participation	Subjective	Satisfaction with democracy (31)	Non-relation	Power	4.70	−0.02				qu	−6.4	0.05
	Values	**Importance of democracy (32)**	**Threshold**	**Power**	**8.4^{***}**	**0.32**	**qu**	**226.8^{***}**	**0.19**	**pl**	**8.1^{***}**	**0.35**
	Objective	**Democracy index (33)**	**Threshold**	**Quadratic**	**357.6^{***}**	**0.34**	**pl**	**14.7^{***}**	**0.27**	**qu**	**17.9^{***}**	**0.45**
General	Subjective	Overall life satisfaction (34)	Non-relation	Power	13.4^{***}	0.21				lin	0.1^{***}	0.38
	Objective	**Human Development Index (35)**	**Threshold**	**Power**	**14.5^{***}**	**0.70**	**qu**	**3.2^{***}**	**0.69**	**qu**	**0.3^{***}**	**0.78**

creativity does not trend with emissions and remains above 70% for most nations (figure 4(a)).

Freedom

Freedom is associated with 11% of the global carbon footprint (figure 2). The subjective satisfaction of *freedom* is the only indicator that shows a linear correlation to *freedom* footprint, however the threshold model offers a comparable good fit (table 4). The finding that 'freedom to choose in life' correlates with its footprint is in line with the capabilities approach by Sen (SI1), who argues that some economic goods that free time, simplify household work or promote synergic need satisfaction, might enable freedom of choice [6, 35]. The importance of *freedom* is fairly high (above 70%) across nations and does not vary with its carbon footprint (figure 4(a)). Institutional freedom stagnates at a value of around 80% of satisfaction corresponding to 1.3 t CO_2eq/cap, pointing to the importance of social institutions in ensuring objective *freedom*, rather than the individual consumption of *freedom*-related goods [5].

Leisure

The importance of *leisure* increases with consumption, suggesting that wealthier societies either tend to perceive less leisure time or value it more [3, 22], despite having similar or slightly more objective free time (see 'expectation-satisfaction gap' in SI). However, this measure does not consider discretionary time by discounting commuting or household work. However, valuing leisure is a trait that emerges in modern societies as they shift towards individualistic values [61]. Noteworthy is that some countries are more eco-efficient than others when satisfying *leisure*: 86% of both Czechs and Danes feel satisfied with their free time at a *leisure* footprint of 1.4 t CO_2eq/cap and 0.86 t CO_2eq/cap, respectively. Objective leisure is rather constant across countries, presumable a consequence of a globalized economy and the influence of organizations such as OECD or International Labor Organization [44, 78] to homogenize labor conditions.

Understanding

We find an association between the carbon footprint of *understanding* and objective satisfaction indicators [24]. The education index displays a strong threshold trend. Nations like Lithuania are able to achieve education coverage above 80% already at a value of 0.04 t CO_2eq/cap, while nations like Turkey and China attain only 55% of education at 0.06 and 0.09 t CO_2eq/cap, respectively (figure 4(b)). We find a weaker yet significant relationship to the improvements in reading skills (PISA) with increases in the carbon footprint of *understanding*. Our results confirm a threshold correlation between consumption and objective *understanding* [24], meaning steeper satisfaction for less wealthy nations. However, subjective satisfaction with learning new things in life and quality of education is not correlated with increased *understanding* emissions.

Participation

All our indicators for *participation* are limited to the concept of democracy. Objective satisfaction with democracy increases until 0.1 t CO_2eq/cap and stagnates, reaching a maximum value of 75%–85% for the democracy index (figure 4(b)) [24]. The importance of democracy seems to display a threshold trend, but this is clearly driven by an outlier (India) when examined visually. In most nations at least 80% of citizens value living under democratic rule. Similar to education, subjective satisfaction with democracy does not trend with emissions. Notably, given the small carbon footprints of *understanding* and *participation*, results for these needs must be interpreted with caution. The satisfaction of these needs is also enabled by broader structural and social factors [3, 61] (see SI 5 for further considerations).

Overall life satisfaction is the only broad subjective indicator that we used to measure QOL. We do not confirm a strong relationship between life satisfaction and total carbon footprint [24, 28–30] but we do find it for energy [25, 79]. This perhaps points to the fact that energy is more reflective of resource inputs, while carbon represents rather an output, linked to the chosen energy carriers. The Human Development Index does confirm the significant and strong threshold shape previously reported [34].

Discussion

Overall, we find stronger support for the 'treadmills of production' theory when testing objective measures of QOL, but insufficient evidence for subjective satisfaction. *Subsistence* and *protection* have the largest footprints (figures 2 and 3), yet the satisfaction of health, financial security and personal safety do not correlate to footprints [5] (table 4, Indicators 1–2, 5–11). The 'treadmills of production' theory argues that consumption levels in the past largely determine consumption in the future, regardless of societal outcomes [12, 16, 80]. Similarly, the concepts of defensive expenditures and false satisfiers are characterized by systematic ecological damage through consumption that fails to satisfy needs (SI1) [7, 11, 16, 80]. This seems to be the case for *subsistence* and *protection*, where rising carbon footprint of health care, insurances or public administration does not correlate with citizens being nor feeling healthier [5] nor safer (see 'urban safety' in SI5).

We generally find greater gains in objective QOL when moving from low to moderate emissions, but diminishing or nil gains at high emissions [7, 17] (see SI5 for further discussion). Moderate increases up to 2 t CO_2/cap in the footprints of *subsistence* and *protection* correspond to steep improvements in the

lowering fertility rates, child survival, access to energy and sanitation [13, 35, 36]. The challenge for governments is to satisfy housing, health, financial and personal security regardless of individual consumption and beyond market offer [5]. Policies that promote work-life balance, healthy lifestyles, universal housing and health, or unconditional basic income are interesting options to lower the carbon burden of *subsistence* and *protection* while enhancing needs satisfaction [18, 22, 39, 43].

We find that rising subjective satisfaction of needs is most likely coupled to what people 'are' and 'do' in wealthier economies, rather than to what they happen to consume or own [2, 11]. Except for *creation* and *freedom*, most indicators of subjective satisfaction do not trend with carbon footprints, as predicted by modernization theories. We rather find correlations among the following indicators of need satisfaction: subjective learning, freedom to choose, creativity and self-expression (SI 4). Satisfaction with creativity at work (*creation*) can enhance the feeling of mastery by using one's full potential on a daily basis [3, 11, 19]. Having vocational skills may play a role in empowering *freedom* of choice for individuals, rather than bearing with circumstances [6, 19]. Interestingly, all subjective satisfaction indicators correlate strongly with overall life satisfaction [19, 31, 44], supporting the importance of individual needs for overall well-being [19, 44, 61].

Policies should tackle subjective satisfaction directly and not solely rely on consumption or objective improvements. Employment structures where people are empowered and develop new skills [19, 56], opportunities for continuous learning [6, 19], and freedom to choose how to spend one's time [7, 22] are all examples of direct satisfiers [7]. Policies could encourage practices that promote intrinsic motivation (instead of materialistic) [81], healthier social norms or 'nudges' to create work and consumption cultures that favor low-impact satisfaction [7, 22, 82]. Bottom-up policies would encourage grassroots initiatives not only to provide sustainable goods–but also to create contexts for social learning [75, 77, 83], cooperation networks and alternative narratives of need satisfaction, such as the de-growth and voluntary simplicity movements [7, 81, 84].

Human ecology factors can potentially influence indicators that display high satisfaction levels but do not trend with footprint. For example, cultural idiosyncrasies or psychological resilience might mediate satisfaction with authenticity or learning new things [19, 61]. Institutional factors might influence residual free time, creativity at work, long-term employment and non-obesity rates [3, 5, 78]. Additionally, the importance of *creation, freedom, identity* and *participation* is high and constant across nations (figure 4), which aligns with the notion that needs are intrinsic and universal [2, 19, 50]. However, we cannot support nor reject the theory of 'human ecology', as we do not explicitly account for such factors [12, 16].

Future work and limitations

Current theoretical frameworks could expand to consider nuances of QOL-impact relationships. For example, support for 'ecological modernization' might be found through territorial footprints but no longer through consumption-accounting of global impact [12, 38, 41, 85, 86]. Similarly, testing development theories through objective or subjective indicators does influence the results, as we confirm here [12, 38]. Theories could further distinguish the roles of resource flows and stocks for environmental and social stewardship [87]. Resource stocks in the form of hospitals or schools might satisfy QOL as predicted by modernization theories [14]. In contrast, military or vehicle infrastructures might lock-in future resources by perpetuating current practices regardless of social outcomes, as predicted by the 'treadmills of production' [80, 87]. Capital formation and infrastructures drive about 24% of yearly global emissions and are currently excluded from our analysis [9, 88]. Theorizing on the role of equity and access to public and private capitals might enrich our understanding of QOL-impact relationships (see 'unit of analysis' in SI6 [35]).

Our study is a cross-sectional analysis based on middle to high income nations for the year 2007, and thus cannot be directly generalized to low-income nations nor extrapolated into the long-term future. We especially expect infrastructure-related indicators, such as access to sanitation and energy, to flatten out as lagging nations reach decent living standards [13]. However, subjective indicators and those related to social institutions are more coupled to cultural values, social dynamics and human behaviors, and are thus harder to predict [24]. The evolution of their trends will largely depend on the effectiveness of country-specific social systems to satisfy needs. Because subjective satisfaction is generally lower, and mental and emotional-related illness are on the rise, currently affecting 6%–27% of individuals across populations [89], monitoring subjective satisfaction in relation to lifestyles becomes increasingly important. Longitudinal case studies which consider contextual information will enable a closer look into the expected relationships between social practices and well-being [41].

Deriving insights from cross-sectional analyses assumes 'modernization pathways', meaning that nations develop by following similar pathways, paved by economic and technological progress [34, 80, 90]. Although this assumption has been supported by studies on societal transitions [13, 34, 38, 41, 61], some leapfrogging nations achieve high human development at a fraction of the resources required by wealthy

nations [24, 26, 34, 90]. We also find that energy and carbon footprints yield similar results, but this might no longer hold in a low-carbon energy future. Future empirical studies could expand by including more nations and testing other environmental indicators such as water or land footprints [24].

Comparing countries through subjective indicators conveys the caveats of cross-cultural analysis [91]. However, data on subjective indicators are increasingly robust and have proven useful [19, 24, 61], as demonstrated by finding different but consistent patterns for objective and subjective satisfaction. While we treat indicators of need satisfaction as independent, some of them are correlated, as we discuss in length in SI4 [3, 5, 19] e.g. better health correlates with living standard. However, we do not investigate the effects of specific goods on QOL nor the efficiency of different market and non-market strategies to satisfy human needs [14, 24]. This remains a key task for future analyses. In SI6 we discuss in detail the validity of our analysis, indicators, limitations, and suggestions for improvement.

Conclusion

At a national level, increasing material consumption entails increasing environmental impact but not necessarily increased QOL. The 'treadmills of production' theory fits our findings of threshold relationships for most objective QOL-carbon footprint relationships, but not for subjective satisfaction. Even if decent material standards tend to be a prerequisite for subjective satisfaction [39, 50], they are not a guarantee [19]. Presumably, consumption has a finite contribution to QOL and once exhausted, satisfaction depends on non-material satisfiers or factors of human ecology [3, 6].

By linking consumption-based footprints and satisfaction through a comprehensive human needs framework [2], we find a richer picture than previously identified through aggregated indicators of QOL [12, 28, 34, 36, 41]. Our conclusion, thus, supports a need-centric approach to sustainability and QOL-impact relationships. The case of *protection* merits special attention, as it drives one fifth of global emissions and yet remains unsatisfied in most dimensions. On the other hand, the general lack of trend between carbon footprint and subjective satisfaction implies the challenge of creating direct low-impact satisfiers. Policy strategies that measure and prioritize human needs would incentivize satisfiers with attractive 'return on investments' in terms of QOL per resource inputs. Through this approach, decoupling the satisfaction of fundamental human needs from environmental damage might become an attainable goal.

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