Type of the Paper (Electronic Supplementary Material)

The three horses of sustainability – population, affluence and technology

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Text S1: The IPAT model

The IPAT equation holds that the total impact of economic and social activity is a function of population size (P), level of affluence (A) and an energy or technology factor (T) [9-11]:

Impact = f (Population, Affluence, Technology Equation (1)

Most simply, population, affluence and technology are multiplied together, providing a strong first approximation of the classic photographs of weekly food consumed in countries with different cultures, but also principally different levels of wealth [30]. The argument is made here at the level of national economies and households in different countries, though it could apply to any entity such as an organization, and individuals.

Population, Affluence (consumption of goods and services) and Technology (or energy/material cost), can and have been framed differently by different authors [14,19,50] (and see main text). Here, Population is given by the world population (fig. S1a). Affluence is approximated by the United Nations Development Programme's (UNDP) Human Development Index (HDI, fig. S1b), where the direct access to ecosystem services and other natural assets in lower income countries (e.g. through local or home production of food) compensates for the mainly market access to these services in richer countries. Technology is approximated by Gross National Income (GNI, fig. S1c), as a proxy for access to and use of energy and manufactured products in richer vs. poorer countries. Quantitative improvements can be made to this parametrization, that also deal better with correlation among the factors, but the focus here is on broad properties [37].

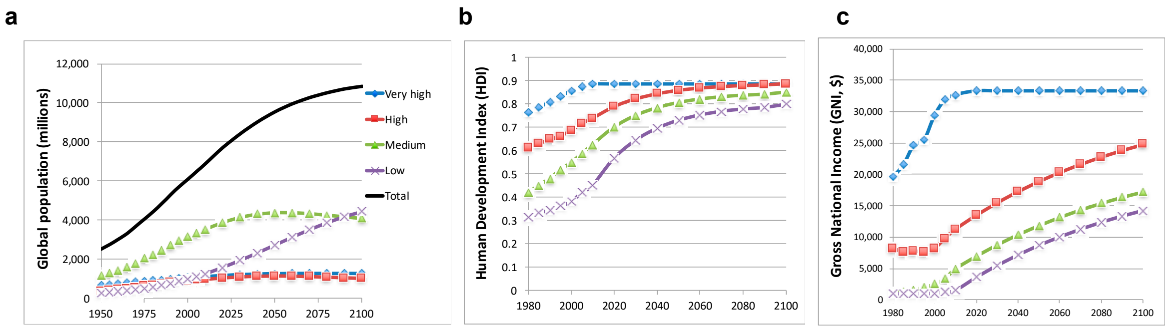

Figure S1. Factors in the IPAT equation - population, affluence and technology. a) global population (in millions), b) Human Development Index (HDI) and c) Gross National Income (GNI, $ per capita) in Very High, High, Medium and Low HDI countries. Impact (IPAT) is a product of these three, see fig. 1. Numbers up to 2015 are measured data, after 2015 are projections [31,32].

The model proceeds on two premises, with three simplifying assumptions:

Premise 1 – countries are at various stages of economic development, expressed by HDI. Four groups are used: Very High (includes US, Europe, Japan, Australia); High (includes Russia, many Middle East states); Medium (includes China, India, South Africa) and Low (most developing and low-income countries) [31].

Premise 2 – country populations can be described by the model of demographic transition [51]. They start at low population densities where birth and death rates are high (stage 1). As affluence increases first death rates decline first (stage 2) then birth rates (stage 3), which results in rapid increases in population growth in stage 2 and into stage 3, due to the differential between these. In stage 4 when affluence is high, birth and death rates equilibrate at low levels, so population growth slows and halts. Finally, in stage 5, at high affluence and ageing populations, death rates may exceed growth rates, resulting in population decline.

Assumption 1 – Population growth is based on median projections established by the United Nations (fig. S1a) [32].

Assumption 2 – Equity – all countries aspire to, and have the right to achieve, equivalent living standards to those experiencing the highest quality of life. Also by this principle countries should not be expected to accept a decline in living standards, so all must eventually converge towards the highest living standards, as currently experienced in Very High HDI and high GNI countries. To simplify calculations, the model caps HDI and GNI at current levels in Very High HDI countries (fig. S1b,c), as projecting these several decades into the future is not possible simply.

Assumption 3 – the principle of 'common but differentiated responsibilities' as accepted in the United Nations Framework Convention on Climate Change [52], holds that effort in reducing total impact should be proportional to current wealth (and this also reflects contribution to past impact) – i.e. wealthier countries adopt higher efficiency targets to reduce their total impact, while poorer countries adopt lower targets, and with later timelines. Over time, as wealth equilibrates across countries, they will converge towards the same efficiency targets.

For this application, the IPAT equation is modified by a coefficient 'e', where e varies between 0 and 1 (0 e < 1; presented in the text as a percentage). e represents a reduction in total impact achieved by reducing population, affluence, or technology, or a combination of these, below reference levels. Thus, (1-e) enables calculation of the resulting Impact. The parameters population, affluence and technology are multiplied together as the most simple expression of the model. The IPAT equation is thus modified to:

Impact = (1-e) * f(Population x Affluence x Technology) Equation (2)

The model is used to consider two basic scenarios (figs. 1a,b), applied through varying the coefficient e (fig. 1c):

Business as usual – current trends in population, HDI and GNI continue into the future. e = 0. Using Assumption 2 to simplify calculations, HDI and GNI are capped at current levels in Very High HDI countries.

Sustainable future – total Impact is capped at 2020 levels, achieved by varying e between 0 and 1. Assumption 3 is applied by applying different levels of e by HDI class such that Very High HDI countries adopt higher and earlier efficiencies than Low HDI countries.

Text S2: exploration of the model factors, limitations and some assumptions for further research

The three major factors each have a fundamental contribution, some key aspects of these being explored in the following text.

Population – the model uses median estimates of population growth, but the same source provides lower and upper confidence limits for growth (fig. S2). At higher growth rates, population will be growing in all income categories in 2100, and Low HDI countries still show accelerating growth rates. At lower growth rates, population in all HDI categories is stabilized and decreasing by 2100, with global population having peaked at under 9 billion in 2050, and declined to under 8 billion, just over today's levels, in 2100. Adjustment of the model to lower population levels (not presented in detail here) lessens the efficiency required from all countries, e.g. from 70 to 50 per cent for Very High and High HDI countries, from 60 to 40 per cent for Medium HDI countries, and from 50 to 30 percent for Low HDI countries, representing significantly less effort needed. By contrast, higher population projections require correspondingly higher reductions in affluence and technology. Of critical importance with respect to political will across all countries is that differentiating these population-based scenarios does not occur until after 2030 in Very High HDI countries and after 2050 in Low HDI countries, a dramatic 10 – 30 year lag that makes garnering political and social commitment to putting in place these long term solutions now extremely challenging.

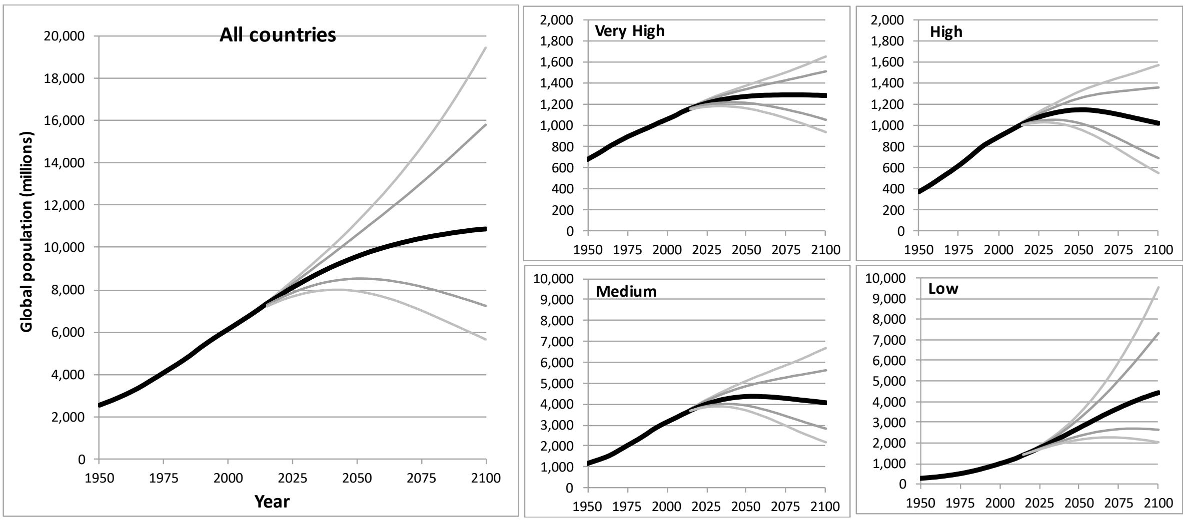

Figure S2. Population growth rates projected by the United Nations for total world population, split by HDI levels: Very High, High, Medium and Low [31,32]. In each figure, the black line shows the median, and the grey lines the 80% and 95% percentile estimates of population.

Affluence - reductions in affluence can occur only with a radical transformation in value systems from the current paradigm that primarily values monetary and material accumulation, to one that values more qualitative and non-material values. Economies and financial markets must no longer exclusively value material growth as the primary measure of wealth. This is recognized in many fields of contemporary writing (see Text S4), and means changing the 'usual' part of 'business as usual', however operationalizing this principle at scale is elusive. Repeated warnings that capital and financial markets have not transformed from the practices that produce repeated 'bubbles' are illustrative of the failure to change what is considered as affluent. Attempts to identify measures other than GDP to measure wealth of countries[1] and of corporations [53,54] are being prototyped. HDI is a step in this direction.

[1] for example, the Gross National Happiness index, http://www.grossnationalhappiness.com/articles/ Accessed 7 February 2016; Human

Technology - reductions in technology impact are perhaps the easiest to implement in that the physical, chemical and biological costs of production and consumption can be dramatically reduced through transforming the way energy and materials are used and recycled. Potential solutions for businesses and the corporate world are currently best expressed in the concept of circular economy[2]. This transforms the linear business model – that extracts natural resources as essentially free goods and emits waste products with limited accounting of their impacts – into a circular one that does two fundamental things. First, it accounts for all raw material inputs from nature, such that all impacts are reduced to zero and/or mitigated in full. Second, waste is reduced to as close to zero as possible by making all outputs an input to another business process, such as in recycling material waste, or scrubbing carbon dioxide from emissions. These are viewed as costs in the linear model and therefore minimized to maximize profit of the business entity; however the costs they impose through pollution (or e.g. climate change) are borne by others, and may be much higher than the initial direct cost. In a circular model they reflect opportunities for investment and further generation of wealth and jobs – in another business, another sector, or in societal or other benefits (e.g. a clean environment).

Further exploration of the premises, assumptions and corollaries of the model is possible (Table S1) but beyond the scope of this paper.

Table S1. Some assumptions and caveats about the model, of interest for further exploration.

Issue	Description
Within-country application	Within countries and economies, similar principles can apply among businesses, income classes and households, to achieve sustainability solutions in an equitable and transparent way.
Current global footprint exceeds 1 planet earth	Though capping affluence and technology at today's levels, the model also provides for potential reductions. The need for greater reduction is explicit in that humanity's footprint today is 1.5 planet earths (WWF 2016), and this needs to reduce to under 1 for true sustainability. This is also illustrated by the need to reduce atmospheric carbon dioxide concentrations from today's level of 407 ppm to below the safe limit of 350 ppm that was passed before 1990 [55].
HDI and GNI cap (Assumption 2)	The assumption that caps HDI at current levels in Very High HDI countries could be relaxed, which would require greater efficiencies to be put in place. However, once transformations in P, A or T are underway, allowing HDI to grow may not have the same impact implications as it currently has.
Measures of affluence and technology	Use of HDI as the measure of affluence, and GNI for technology rather than affluence, may be debatable and provides avenues for improved parametrization of this model.
Does reducing impacts cost?	One assumption embedded within the principle of common but differentiated responsibilities (Assumption 3) is that there is a cost to reducing impact. This may not always be the case, as there may be multiple and broader benefits that stakeholders may obtain from more equitable approaches to reducing impact that transforms apparent costs into benefits, and this may be true for both richer [56] and poorer countries [57]. Further,

Development Index (HDI), United Nations Development Programme (UNDP) - http://hdr.undp.org/en/content/human-development-index-hdi [Accessed 7 February 2016].

[2] See https://www.ellenmacarthurfoundation.org/circular-economy/overview/concept (accessed 10 August 2016) and http://www.circularecology.com/ [accessed 10 August 2016]

	costs associated with reduction of impacts at source may be less than costs associated with those impacts borne by broader society, but not well-costed or accurately attributed, so this may be a matter of just attribution of costs.

The IPAT model has been debated extensively in the past and does have its weaknesses. These are summarized as follows [58]: "IPAT itself has been criticized because it does not account for interactions among the terms (e.g., increasing affluence can lead to more efficient technologies); it omits explicit reference to important variables such as culture and institutions (e.g., social organization); impact is not linearly related to the right side variables (there can be important thresholds); and it can simply lead to wrong conclusions." The intent here is not to ignore these problems, as they can be addressed in specific circumstances. Rather, the intent is to return to a simpler expression of causal relationships [37] that through their relevance and accessibility to people, businesses and politics, can stimulate behaviour change [8].

Text S3 Estimating impact from images of household weekly food intake

Images household weekly food intake [30] were downloaded and the data derived from them (Table S2). Various formulations of the IPAT equation were trialed (Table S2), with trial D being retained as being most descriptive of the information content of the images. These values are used in fig. 2, assigned to the year 2020.

Table S2. Data obtained from images of household weekly food intake (Menzel 2013).

Variable	Description	Value
Metadata		
Continent	Continent, based on country name	Text
Country	Country name	Text
City	City name assigned to image	Text
Photo Code	Image label, from image metadata	Label
Data obtained from images		
People	Number of people present in the image	Number
Food Expenditure ($)	Weekly food expenditure published with each image	Value ($)
Food cost per person ($)	Weekly food expenditure divided by the number of people per household	Value ($)
Food types	Sum of food types in each image. Each major item scored as: 1-vegetable/grain; 2-fish/aquatic; 3-meat/dairy; 4-Other (pizza, biscuits, wine, alcohol, crisps, chocolate, sugary drinks); and all these scores summed.	Number (sum of ranks/scores)
Packaging	Sum of packaging types in each image. Each major item scored as: 1- cardboard/cartons/glass ; 2- tins /plastic (reusable)/cans; 3- plastic single use; and all these scores summed.	Number (sum of ranks/scores)
Classification variables		
GDP per capita	Gross Domestic Product, obtained from	Value ($)
HDI	HDI country category derived from UNDP (2015), for consistency with the years of data analyzed and photos (prior to 2013)	Index (0-1)
HDI group	Categories: Low, Medium, High, Very High; as classified by UNDP (2015)	Category
Technology	Sum of the energy source used in all appliances in the image (1-biomass; 2-gas; 3-electricity)	Number (sum of ranks/scores)

Examples of IPAT parametrizations attemped		
Trial A	People * GDP * Technology	Index (scaled from 0-100, where 100 is the maximum country score obtained)
Trial B	People * Food types * Packaging	
Trial C	People * Food cost per person * Packaging	
Trial D	People * cost per person * (Food types + Packaging + Technology)	

To project the values of household impacts to 2030 and 2100 in accordance with model (figs. 2b,c), assumption 2 was parametrized as follows: economic growth was accommodated by setting long term growth rates by HDI group that would enable eventual parity. These were selected arbitrarily as: Low HDI - 5%., Medium HDI – 2%, High HDI – 1 % and Very High HDI – 0%. Projected impact was calculated by multiplying the mean value for each HDI group (from fig. 2a) by compounded growth to 2030 and 2100, and the relevant reduction coefficient. This analysis is plotted in figs. 2b & c.

Text S4 Illustrative citations on the call for transformative change

A wide variety of sources including government, global media and online fora, illustrate the widespread acknowledgement of the need for radical transformation to enable sustainability. Some examples include:

- UNGA (2012) Resolution adopted by the General Assembly on 27 July 2012 A/RES/66/288. The future we want. Accessed at http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/66/288&Lang=E 1 December 2015;
- The Economist (2012) Boundary conditions. The idea of planet-wide environmental boundaries, beyond which humanity would go at its peril, is gaining ground. The Economist, Jun 16th 2012. Accessed at http://www.economist.com/node/21556897 7 February 2017;
- Gillis, Justin (2012) Are We Nearing a Planetary Boundary? International New York Times, June 6, 2012, https://green.blogs.nytimes.com/2012/06/06/are-we-nearing-a-planetary-boundary/, accessed 1 February 2017;
- Revkin, Andrew C. (2015) Can Humanity's 'Great Acceleration' Be Managed and, If So, How? International New York Times January 15, 2015. https://dotearth.blogs.nytimes.com/2015/01/15/can-humanitys-great-acceleration-be-managed-and-if-so-how/, accessed 1 February 2017;
- The Millennium Alliance for Humanity and the Biosphere, https://mahb.stanford.edu/
- The Secretary-General to the UNFCCC, Mr. Antonio Gutierrez, on 12 December 2018, at the closing of the High-Level Segment of the Talanoa Dialogue, COP-24, imploring country delegations to generate the consensus needed to assure the appropriate levels of ambition are achieved in committing the finance and 'rulebook' necessary to achieve the Paris Agreement. [as delivered, 12 December 2018]. https://www.un.org/sg/en/content/sg/statement/2018-12-12/secretary-generals-remarks-the-closing-of-the-high-level-segment-of-the-talanoa-dialogue-cop-24-delivered.

References

See in main text.