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A good life for all within planetary boundaries

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1 Theoretical Framework

1.1 The Ends–Means Spectrum

The analytic framework that we adopt in our analysis (Fig. 1 of main text) is a variation of the Ends–Means Spectrum (EMS) originally proposed by Herman Daly in the early 1970s[1]. The EMS organises items in a continuum from *ultimate means* (the natural resources that sustain life and all economic transactions), to *intermediate means* (the factories, machines, and skilled labour that transform natural resources into products and services), to *intermediate ends* (the goals that the economy is expected to deliver), to *ultimate ends* (those goals that are desired only for themselves, and are not the means to achieve any other end).

Donella Meadows proposed using the EMS to create a coherent information system for sustainable development[2]. She argued that sustainable development is "a call to expand the economic calculus to include the top (development) and the bottom (sustainability)" of the framework (p. 44). The EMS has previously been used to create a system of indicators to measure how close countries are to the idea of a "steady-state economy"[3,4], which was later extended to include the concept of planetary boundaries[5]. It has also been used to interpret the Sustainable Development Goals, and organise them according to the ecological economics policy objectives of sustainable scale, fair distribution, and efficient allocation[6]. Our work here goes beyond previous applications of the framework in two important ways: (i) it conceptualises intermediate means in a broad sense as "physical and social provisioning systems", and (ii) it describes intermediate ends in terms of a theory of basic human needs.

1.2 Provisioning Systems

We use the term "provisioning systems" to describe the physical and social systems that link the production, distribution, and consumption of the goods and services through which human needs are satisfied. Within our analytic framework (Fig. 1), provisioning systems form the bidirectional link between biophysical resource use and social outcomes.

The concept of provisioning systems arises from heterodox traditions in economics, and can be traced back to Aristotle, who considered pure for-profit market activities to be "chrematistics", whereas the broader "oikonomia" focused on the "art of living and living well"[7]. In 1987, Gruchy crystalised this understanding by stating that "economics is the study of the on-going economic process that provides the flow of goods and services required by society to meet the needs of those who participate in its activities… [Economics is] the *science of social provisioning*" (p. 1099)[8].

Much earlier, in 1968, Polanyi famously stated:

> [The economy is] an instituted process of interaction between man and his environment, which results in a continuous supply of want-satisfying material means… The human economy, then, is embedded and enmeshed in institutions, economic and noneconomic. The inclusion of the noneconomic is vital. For religion or government may be as important for the structure and functioning of the economy as monetary institutions or the availability of tools and machines themselves that lighten the toil of labour (p. 1099)[8].

Polanyi's statement is notable both because it acknowledges the material and environmental aspects of provision, and also because it emphasises the "non-economic" aspects of provisioning, including social relations, power structures, culture, and so on. Following Polanyi, our analytic framework highlights both the material (physical/technical aspects) and social dimensions of provisioning systems.

We include provisioning systems as a conceptual intermediary between planetary processes and human well-being, and thus ascribe some of the variation in international performance to differences in underlying provisioning systems. Research into provisioning systems entails substantial challenges, in terms of setting system boundaries, as well as integrating multiple disciplinary perspectives (e.g. economics, sociology, political science, and engineering). Nevertheless, we argue that a better understanding of these systems may be particularly helpful for opening up the "black box" that has to date remained at the heart of research into the links between resource use and social outcomes.

1.3 Basic Needs

The report of the World Commission on Environment and Development (i.e. the Brundtland Report[9]), famously defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The report goes on to say that sustainable development "contains within it two key concepts: the concept of 'needs'… and the idea of limitations" (p. 43).

It is important to note that the Brundtland Report does *not* say that sustainable development is about "satisfying wants" or "increasing economic welfare" or even "improving well-being". The definition is focused on needs, and therefore a coherent framework for understanding human needs is critical to achieving sustainable development, if defined in this way[10,11].

Two theories of human needs, both developed in the early 1990s, are particularly helpful in this regard. The first, described by Manfred Max-Neef in his book *Human-Scale Development*[12], argues that human needs are "finite, few, and classifiable". Max-Neef suggests that there are nine fundamental human needs: subsistence, protection, affection, understanding, participation, leisure, creation, identity, and freedom. While these needs are claimed to be universal, the way that they are satisfied may vary among cultures and over time. For instance, the need for subsistence may be met with a variety of different forms of food and shelter. For this reason, Max-Neef makes the important distinction between "needs" (which are seen as universal) and "need satisfiers" (which are not).

The second theory, proposed by Len Doyal and Ian Gough in their book *A Theory of Human Need*[13], argues that the universal goal (or ultimate end) of human activity is "minimally impaired social participation". Two basic needs (physical health and autonomy of agency) are identified as critical to achieving social participation. Autonomy of agency is further subdivided into mental health, cultural understanding, and opportunities to participate. Similar to Max-Neef, the authors claim that basic needs are universal, but the way they are satisfied may vary depending on institutions and culture. However, they suggest that need satisfiers have certain "universal characteristics", which apply to all cultures, and which can be determined empirically. For instance the need for food may be satisfied by many different diets (all of which are need satisfiers). The universal characteristic of all of these diets, however, is their calorific content, for which human beings have common requirements.

Doyal and Gough go on to identify 11 "intermediate needs" (the equivalent of Daly's intermediate ends) based on these universal characteristics. These needs are nutritional food and clean water, protective housing, a non-hazardous work environment, a non-hazardous living environment, appropriate healthcare, security in childhood, significant primary relationships, physical security, economic security, safe birth control and child bearing, and basic education. Importantly, Doyal and Gough also claim that these intermediate needs are satiable and non-substitutable, a conceptualisation that is consistent with the paradigm of strong sustainability. As Ian Gough puts it, "More education is of no help to someone who is starving. Human needs are irreducibly plural" (p. 1201)[10].

That said, theories of human need are commonly criticised on two grounds. First, they face claims of paternalism, being derived by experts and academics, with little apparent recourse to individual desires and sovereignty over life-choices. Second, a project to define universal human attributes is seen as impossible by many, due to the relative, historical, and socially constructed nature of individual needs. In responding to these issues, much emphasis has been placed on the separation of needs and satisfiers—or in the work of Amartya Sen and Martha Nussbaum, the separation of "functionings" and "capabilities"[14,15]. Since the normative political goal is focused on extending satisfiers and capabilities (i.e. the ability to fulfil needs, not the fulfilment itself), the central importance of individual choice can be preserved[16]. The counterfactual also remains important: by failing to collectively define human needs through an open scientific and public discourse, powerful vested interests may choose to do so instead, and to their own benefit—as can be seen through the pervasive impact of contemporary advertising on individual consumer preferences[10]. Finally, both Nussbaum[15] and Doyal and Gough[13] have extensively addressed arguments against universalism. They discuss, for instance, the non-desirability of many need-constraining cultural practices, and the objectively disabling nature of serious health disorders across all cultures.

1.4 A Safe and Just Space

The theory of human needs developed by the above authors underpins the approach taken by Kate Raworth in her "safe and just space" (SJS) framework[17]. The SJS framework brings together the notion of an "environmental ceiling" (as defined by planetary boundaries), with a "social foundation" (defined by basic needs). The idea is that resource use should remain within this space. In other words, it should be high enough to meet people's needs (above the social foundation), but not so high as to transgress planetary boundaries (below the environmental ceiling).

As Raworth explains, both the social foundation and environmental ceiling are normative boundaries:

> What constitutes human deprivation is determined through widely agreed social norms. Likewise, although science focuses on giving an objective description of the planet's biophysical reality, the question of where to set the boundaries of natural resource use is ultimately a normative one, based on perceptions of risk, and desirability of staying within the Holocene (p. 8)[17].

For this reason, Raworth based her choice of which objectives to include in the social foundation on the submissions of national governments to the Rio+20 Conference on Sustainable Development. Out of a total of 80 submissions, she identified 11 social priorities mentioned in at least half of the submissions. These priorities also overlap substantially with the Sustainable Development Goals (see Supplementary Table 5), which is not surprising given that the conference launched the process to develop the goals. While the basic needs identified by Raworth[17] are arguably not as theoretically consistent as those put forward by Max-Neef[12] or Doyal and Gough[13], they are more democratic (reflecting as they do the concerns of democratically-elected governments), and closely aligned with contemporary policy.

Since its creation, the SJS framework has attracted considerable interest from various organizations including the UN General Assembly[18], think tanks[19,20], and development agencies[21], and led to academic studies that have attempted to operationalise it at the regional and national scales[22,23].

Given its wide applicability, we adopt the SJS framework as the conceptual framework governing the choice of indicators in our analysis. We organise these indicators according to the Ends–Means Spectrum, however, which serves as our analytic framework. The EMS is necessary to understand and interpret the relationship between indicators, which the SJS framework is silent on. The result is a set of national indicators that includes both planetary boundaries and basic human needs, as well as a framework for understanding the relationship between these.

2 Downscaling Planetary Boundaries

2.1 Climate Change

The planetary boundary for climate change is generally expressed as a maximum concentration of CO_2 in the atmosphere of 350 ppm, a value that would likely preserve the climate in a Holocene-like state[24]. Atmospheric CO_2 concentrations currently exceed 400 ppm[25]. Due to inertia in human energy systems, and in the Earth-system response to decarbonisation, it is generally regarded as unlikely that atmospheric CO_2 can be brought below 350 ppm in the 21st century; even the most optimistic integrated assessment scenarios considered in the IPCC's Fifth Assessment Report (AR5) only achieve a range of 420–440 ppm by 2100[26,27]. To have an actionable target, it seems likely that a new (non-Holocene) climate state must be accepted—one that avoids the worst impacts of a changing climate, but allows for a reasonable chance for societies to decarbonise. How to set such a target has been one of the defining discourses in climate research and international policy[28].

As an alternative boundary to 350 ppm, we use the 2 ^{o}C temperature stabilisation goal emphasised in the Paris Agreement[29]. The cumulative emissions from 2011 to 2100 associated with a "high" probability (66%) of achieving this goal are approximately 1000 Gt CO_2, or given a population of 7 billion people, approximately 1.61 t CO_2 per capita (assuming CO_2 emissions available in the 2011–2100 carbon budget are distributed uniformly over time). A number of factors could increase, or decrease, this number. For instance, a large uptake of negative emissions technologies might increase the overall budget, and thus the per capita allowances, but such technologies come with inherent biophysical, technological, and economic risks[30,31]. Conversely, the per capita boundary might be reduced by an increase in population, the absence of stringent mitigation after 2011, the (probable) absence of mitigation before 2020, or a shift in political ambition (e.g. towards the 1.5 ^{o}C target). Accordingly, 1.61 t CO_2 per capita is likely to be a conservative estimate.

To estimate national performance in relation to this per capita boundary, CO_2 emissions data were obtained from the Eora multi-region input-output (MRIO) database (http://worldmrio.com)[32,33]. These data represent the consumption-based allocation of CO_2 emissions from energy production (excluding biomass burning) and cement production, where emissions embodied in imports and exports are added or subtracted, respectively, from national accounts.

2.2 Biogeochemical Flows

The planetary boundaries framework provides two sub-boundaries for biogeochemical flows, one for the phosphorus cycle and the other for the nitrogen cycle. The planetary boundary for phosphorus is 6.2 Tg P y^{-1} mined and applied to erodible (agricultural) soils[24], which we divided by world population to arrive at a per capita boundary of 0.89 kg P y^{-1}. National phosphorus footprint data were obtained from the Eora MRIO database[32,33], and represent the consumption-based allocation of phosphorus fertilizer applied to cropland. The underlying phosphorus fertilizer data were compiled by Potter et al.[34], and are available from the NASA Socioeconomic Data and Applications Center (SEDAC)[35]. The phosphorus data are based on estimates of harvested area for the period 1997–2003 and fertilizer application rates for the period 1994–2001.

To account for the difference in time periods between the phosphorus data (ca. 2000) and the year considered in this study (ca. 2011), the phosphorus data were scaled to match current global phosphorus use (14.2 Tg P y^{-1}) as reported by Steffen et al.[24] For example, global phosphorus use is 10.0 Tg P y^{-1} according to the Eora database, which is lower than the estimate by Steffen et al. Thus country values were multiplied by a factor of 14.2/10.0 to account for the difference in time period and calculation methodologies. The adjusted Eora data were compared to phosphorus footprint data from a more recent study by Metson et al.[36]. The two data sources yielded similar results, and so we have used the Eora data in order to apply a consistent approach to international trade.

The planetary boundary for nitrogen is 62 Tg N y^{-1} from industrial and intentional biological fixation[24], which we divided by world population to arrive at a per capita boundary of 8.9 kg N y^{-1}. National nitrogen footprint data were obtained from the Eora MRIO database[32,33], and represent the consumption-based allocation of nitrogen fertilizer applied to cropland. The underlying nitrogen fertilizer data were compiled by Potter et al.[34] in the same way as the phosphorus data, and are available from SEDAC[37]. Similar to phosphorus, the nitrogen data were scaled to match current global nitrogen fixation (150 Tg N y^{-1}) as reported by Steffen et al.[24]

2.3 Freshwater Use

The original planetary boundary for freshwater use was specified as a maximum global withdrawal of 4000 km^3 y^{-1} of blue water from rivers, lakes, reservoirs, and renewable groundwater stores[38]. This boundary has been debated, both in terms of the level at which it is set[39], and also in terms of its relevance and scientific rigour, given that the environmental impacts of freshwater use are primarily confined to the river-basin scale[40].

With the recent update to the planetary boundaries framework[24], the global boundary remains the same as originally proposed, but it has been complemented with a basin-scale boundary in recognition of the heterogeneity in hydrological characteristics of river basins around the world[41]. The proposed basin-scale boundary draws on the concept of minimum "environmental flow requirements" to maintain healthy riparian/coastal ecosystems and also takes into account seasonal variation in freshwater availability by tracking monthly flows[42]. We believe it is important to take into account the spatial and temporal variation in freshwater availability, but we are unaware of any monthly, basin-scale data that also account for international trade of water-intensive products (i.e. virtual water flows).

Due to the above data limitation, we explored two additional methods to attribute per capita freshwater boundaries to nations (alongside the global boundary currently estimated in the planetary boundaries framework). The first method extended a monthly basin-scale measure that we had previously applied to Canada and Spain[5] to nearly 150 countries using data from Hoekstra et al.[43], but the resulting territorial indicator was not consistent with our consumption-based analysis. The second method was a bottom–up approach that upscaled basin-level environmental flow requirements to a global aggregate of 2800 km^3 per year[39], which is notably less than the global boundary in the planetary boundaries framework. However, this upscaling method also yielded a smaller estimate of global freshwater consumption (1700–2270 km^3 y^{-1}) compared to the top–down estimate of 2600 km^3 y^{-1} from Steffen et al.[24] As a result, the estimate from the planetary boundaries framework that humanity is currently consuming 65% of the global freshwater boundary is fairly similar to the central estimate of 71% using the bottom–up approach (and within the uncertainty range of 61–81%).

Based on the above comparison of methods, we decided that the global boundary of 4000 km^3 y^{-1} from the planetary boundaries framework was the most appropriate for our purposes, although we note that the literature is still evolving. We divided this boundary by world population to arrive at a per capita boundary of 574 m^3 y^{-1}. National water use data were obtained from the Water Footprint Network[44], and are an average for the period 1996–2005 (the most recent period available). The data measure the consumption and pollution of blue water related to the domestic water supply, plus virtual-water imports, minus virtual-water exports (and are thus a measure of apparent consumption). Similar to the data for biogeochemical flows, the blue water data were scaled to match current global freshwater use (2600 km^3 y^{-1}) as reported by Steffen et al.[24]

2.4 Land-System Change

The original planetary boundaries framework[38] proposed the percentage of global land cover converted to cropland as a measure of change in land use, and proposed a boundary of a maximum of 15% of ice-free land being used for crops. Globally this translates into 1995 Mha, or about 0.3 ha per capita[45]. With the recent update to the planetary boundaries work[24], the land-system change boundary is now defined in terms of the amount of forest cover remaining. The boundary is set differently depending on forest biome, but works out to maintaining a minimum of 75% of global original forest cover. Although in principle it would be possible to estimate a per capita boundary associated with global forest cover, and a comparable national indicator, we take a different approach here for two reasons: (i) the distribution of forests (and the use of forest products) varies substantially among countries, and (ii) the area of forested land associated with the consumption of goods and services is a crude (and difficult to measure) indicator.

Instead, we use a more nuanced indicator, namely "human appropriation of net primary production" (HANPP), which has been proposed as an alternative planetary boundary that integrates four of the current boundaries[46]. These boundaries are land-system change and biosphere integrity, in particular, but also freshwater use and biogeochemical cycles to some degree. HANPP 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[47]. It may be compared to the potential net primary production (NPP_{pot}) that would exist in the absence of human activities, to arrive at a useful planetary boundary. It has been suggested, for instance, that HANPP should not exceed 20% of NPP_{pot} (ref. [48]), although there is little scientific rationale for this particular threshold.

As a planetary boundary for HANPP, we use a more robust estimate that only 5 Gt C y^{-1} of NPP_{pot} remains available for appropriation by humans[46]. National HANPP data were obtained from Kastner et al.[47] for the year 2007 (the most recent year available), and measure the *embodied* human appropriation of net primary production (eHANPP). These data reflect the consumption-based allocation of HANPP to final biomass products from agriculture and forestry, where trade is accounted for using physical bilateral trade matrices. According to these data, global eHANPP was 13.2 Gt y^{-1} in 2007, which is about 10% lower than other published data (e.g. ref. [49]) because the consumption-based data do not include human-induced vegetation fires or the land occupied by infrastructure. We therefore estimate the planetary boundary for eHANPP to be 13.2 + 5.0 = 18.2 Gt C y^{-1} (excluding human-induced fires and infrastructure). This value yields a per capita boundary of 2.62 t C y^{-1}, which is roughly equivalent to setting the boundary at 33% of NPP_{pot}.

We acknowledge that although the new boundary for land-system change defined by Steffen et al.[24] is currently being transgressed, the global boundary for eHANPP is not[46]. In part this reflects the difference between a stock-based indicator (forest area) and a flow-based indicator (eHANPP), as well as the inclusion of agriculture within eHANPP. Given these differences, the boundary based on eHANPP may be viewed as less strict than the boundary based on forest area defined by Steffen et al.[24]

2.5 Ecological Footprint

The ecological footprint measures how much biologically productive land and sea area a population requires to produce the biotic resources it consumes and absorb the CO_2 emissions it generates, using prevailing technology and resource management practices[50]. It is the sum of six components (cropland, forest land, fishing grounds, grazing land, built-up land, and carbon land), and may be compared to biocapacity (the total available area of biologically productive land and sea area). Although widely used, the ecological footprint has also been widely criticised[51-53]. A review of the footprint based on a survey of 34 internationally-recognised experts and an assessment of more than 150 papers concluded that the indicator is a strong communications tool, but that it has a limited role within a policy context[54]. Three frequently-cited criticisms of the ecological footprint include: (i) comparing a nation's total footprint to its national biocapacity introduces an anti-trade bias that is particularly unfair to small countries[51,52]; (ii) the method used to translate CO_2 emissions into land area (which is based on the hypothetical forest area required to assimilate emissions) exaggerates the size of the footprint, as more land-efficient methods could be devised[53]; and (iii) as an aggregated indicator of resource use with a single sustainability threshold, the footprint provides no information on when specific ecological limits might be reached[54].

Nevertheless, the ecological footprint remains a well-known indicator of strong sustainability that is frequently cited in studies questioning the sustainability of global resource use[55]. We therefore include it for comparison with the downscaled planetary boundary indicators. However, we address the first criticism by only comparing a country's per capita ecological footprint to an equal per capita share of global biocapacity. The other two criticisms remain, but carry somewhat less weight in our analysis given that the footprint is used alongside indicators for specific ecological limits (i.e. the planetary boundaries).

Per capita ecological footprint data and global biocapacity data were obtained from the Global Footprint Network[56]. The ecological footprint data account for trade by adding imports and subtracting exports (resulting in a measure of apparent consumption). The data indicate that the world average footprint is 2.65 global hectares (gha) of land per capita, which is 50% above global biocapacity of 1.72 gha per capita.

2.6 Material Footprint

The material footprint, also known as "raw material consumption" (RMC), measures the amount of used material extraction (minerals, fossil fuels, and biomass) associated with the final demand for goods and services, regardless of where that extraction occurs. It includes the upstream (embodied) raw materials related to imports and exports, and is therefore a fully consumption-based measure[57]. Like the ecological footprint, it is an indicator of strong sustainability that does not link directly to a planetary boundary. However, we include it in our analysis as material use is an important indicator of the environmental pressure exerted by socioeconomic activities[58], and a maximum sustainable level has been proposed by various authors[55,59-61].

For instance, Dittrich et al.[59] suggest that global material extraction should not exceed 50 Gt y^{-1}, and propose a per capita limit of 8 t y^{-1} by 2030. This limit was also adopted in a high-profile analysis of the sustainability of humanity's environmental footprint[55], while UNEP's International Resource Panel recommends a per capita target of 6–8 t y^{-1} by 2050[61]. A more recent analysis by Bringezu[60], which uses higher population growth projections, suggests a per capita target value of 5 t for the year 2050, with a range of 3–6 t. This target value is based on a return to year 2000 material use, which was 50.8 Gt. We adopt a global target of 50 Gt y^{-1}, as it is a common denominator in all the analyses, although we caution that the literature is not very mature in this area. This value leads to a per capita target of 7.2 t y^{-1}, assuming a world population of 7 billion people. National material footprint data were obtained from the Eora MRIO Database[32,33], based on the study by Wiedmann et al.[57], and are for the year 2008 (the most recent year with complete data).

2.7 Other Boundaries

Biosphere integrity is not explicitly included in the analysis due to the large difficulty in measuring and downscaling both functional and genetic diversity. It is represented, to some degree, however by the indicator used to measure land-system change (i.e. eHANPP). The stratospheric ozone depletion boundary is expressed as a <5% reduction in stratospheric ozone concentration. This boundary could theoretically be included in a similar way to the climate change boundary (e.g. based on the targets of the Montreal Protocol). However, we have not included it because (a) the emission and management of ozone-depleting substances lies outside the scope of the decision-making of the average person, and (b) the Antarctic ozone hole is recovering as a result of the Montreal Protocol[62]. Ocean acidification is not included as a separate boundary since it is driven by climate change, and thus the corresponding pressure indicator (i.e. CO_2 emissions) is already fully accounted for in the analysis. According to Steffen et al.[24], the ocean acidification boundary "would not be transgressed if the climate-change boundary of 350 ppm CO_2 were to be respected".

3 Establishing Social Thresholds

3.1 Life Satisfaction

There are a number of different approaches to measuring subjective well-being. The most widely used in practice is probably the life satisfaction (or evaluative) approach, which relates well-being to an individual's subjective appraisal of how his or her life is going[63]. Evaluative measures may range from a single question about life satisfaction, to multiple questions about different aspects of a person's life. In our analysis, we use a single life satisfaction measure known as the Cantril life ladder. The data are from the Gallup World Poll, as published in the *World Happiness Report*[64]. The English-language wording of the question is: "Please imagine a ladder, with steps numbered from 0 at the bottom to 10 at the top. The top of the ladder represents the best possible life for you and the bottom of the ladder represents the worst possible life for you. On which step of the ladder would you say you personally feel you stand at this time?"

A value of 6.5 out of 10 was chosen to represent the minimum threshold for this indicator. This value is slightly lower than the 7 out of 10 value that is often chosen to indicate a "high" level of human well-being[65]. The lower threshold was used here because scores derived from the Cantril ladder question were found to be 0.5 points lower on average than scores derived from the question used by many statistical agencies (a variant of "Overall, how satisfied are you with your life nowadays?")

3.2 Healthy Life Expectancy

We measure physical health using "healthy life expectancy at birth" (HALE), an indicator that measures the number of years that an individual is expected to live in good health (without major debilitating disease or infirmity). This indicator is extremely closely related to life expectancy at birth: HALE is on average 9 years lower than overall life expectancy, with a standard deviation of 1. We have set the lower HALE boundary at 65 years of healthy life. Although this threshold might seem on the high side, it is within grasp of most countries. In 2011, 40% of the countries for which data were available for this indicator had already achieved the threshold. Moreover, life expectancy is increasing in many countries at a rate that outpaces both economic and resource use growth, suggesting that high healthy life expectancy can be achieved at lower levels of resource use over time[66]. We use HALE data calculated by the authors of the *World Happiness Report*[64], which are based on data from the World Health Organization, World Development Indicators, and statistics published in academic articles.

3.3 Nutrition

We measure nutrition using the "food supply" indicator compiled by the UN Food and Agriculture Organization[67]. This indicator is measured in kilocalories (kcal) per capita and per day, and represents an average calorific intake of food and drink. The physiological requirements for the average adult range between 2100 and 2900 kcal per day (for average women and men and moderate physical activity). However, the calorific requirements associated with heavy manual labour or athletic activity can exceed these levels substantially[68]. An average of 2500 kcal per person per day can thus be considered an individual minimum average level. We have used 2700 kcal per person per day as a population-wide threshold, to allow for some inequality in distribution, since a significant fraction of the population eating a larger share of food could result in a significant fraction facing undernourishment or hunger below this level[69,70].

3.4 *Sanitation*

The sanitation indicator in our analysis measures the percentage of the population using improved sanitation facilities. A staggering 2.4 billion people, or 35% of the global population, currently lack access to improved sanitation facilities, with nearly 1 billion people practicing open defecation[71]. Raworth[17] argues from a rights-based approach that 100% of the population should have access to improved sanitation because it is a fundamental aspect of a life free of deprivation. The target adopted in the Millennium Development Goals was to halve the proportion of people living without improved sanitation by 2015[72], which would have provided access to about 80% of the global population had it been achieved. Although we believe that 100% of the population should have access to improved sanitation facilities, we have chosen a threshold of 95% for this indicator in recognition of the difficulty associated with extending universal access to the last 5% of a population, often located in very rural areas (few countries have actually achieved this goal). The data used in our analysis are from the World Bank's *World Development Indicators*[73].

3.5 *Income*

The very first target specified in the Sustainable Development Goals is to "eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day"[74]. We adopt this well-known measure as our income indicator, but use the latest World Bank data which define the poverty threshold at $1.90 a day using 2011 international prices[73]. Although we use this standard indicator, we also recognise that many argue this threshold is too low[75]. Given that the data are relatively sparse and not available for most high-income countries, we calculated the average value over three years (2010–2012), and made the assumption that high-income countries (as defined by the World Bank) where no data are provided have achieved the target of eradicating extreme poverty. Although the goal is clearly to have 100% of the population living above the $1.90 a day line, we use a threshold value of 95% in our analysis, given that not many countries report this indicator above 95%. In effect, we assume that values above 95% are equivalent to eradicating extreme poverty.

3.6 *Access to Energy*

Around 1.1 billion people currently do not have access to electricity. Another 2.9 billion people rely on wood or other biomass to cook food, resulting in 4.3 million deaths per year that are attributable to indoor air pollution[76]. The data used in our analysis measure the percentage of the national population with access to electricity. They were obtained from the World Bank's *World Development Indicators*[73], and are for the year 2012 (data for 2011 were not available). Similar to the other percentage indicators, a threshold of 95% electricity access was used.

3.7 *Education*

Secondary school enrolment was chosen as our education indicator. We focused on secondary education for two reasons. First, without receiving more subject- or skill-oriented instruction during their teenage years, not only are young people ill-prepared for tertiary education or the workforce, but they are also more at risk of activities with negative effects on well-being such as juvenile delinquency, teenage pregnancy, and radicalisation by militants[77]. Second, secondary education has the potential to dramatically reduce population growth based on evidence suggesting that women in developing countries who complete secondary education average at least one child fewer per lifetime than women who only complete primary education[78]. The data used in our analysis measure gross enrolment in secondary education (i.e. the ratio of total enrolment, regardless of age, to the population that are of secondary-school age). Ideally we would have used net enrolment data (i.e. the ratio of enrolled children who are of secondary-school age, to the population that are of this age). However, these data were not available for enough countries. The gross enrolment data that we have used are from the World Bank's *World Development Indicators*[73]. Similar to the other percentage indicators, a threshold of 95% was chosen for this indicator, in recognition that universal access to education does not imply 100% enrolment.

3.8 Social Support

The importance of social support for achieving long, happy, and healthy lives was firmly established nearly half a century ago[79]. The social support indicator used in our analysis is a measure of whether or not people have someone to count on in times of need. It is the national average of binary responses (either 0 or 1) to the question "If you were in trouble, do you have relatives or friends you can count on to help you whenever you need them, or not?" The data are from the Gallup World Poll, as published in the *World Happiness Report*[64].

A value of 0.9, or 90%, was chosen as the minimum threshold for this indicator. This choice, which is lower than the other percentage indicators, was based on our identification of two confounding factors that suggest a small share of negative responses to the above question may be acceptable. First, reducing the complexity of a respondent's close relationships into a simple yes/no question likely leads to responses based on the availability heuristic, which is biased towards emotionally charged memories[80]. Second, the data do not differentiate between long-term, involuntary social isolation and short-term lack of social support. Lack of support in the short term can arise due to changing circumstances, which may be voluntary (i.e. moving to a new region for work). Although long-term lack of support unambiguously exacts a high social cost, short-term lack of support is arguably not a major policy concern.

3.9 Democratic Quality

Democracy is a collection of norms, institutions, and organisational arrangements from which individuals and communities exercise power over their collective governance. While guarding against discourses that reinforce structures of elite power[81,82], democratic rights such as free association, free speech, and transparent policy-making are vital for enabling social participation and personal autonomy[13]. Following the approach taken in the *World Happiness Report*[64], the indicator of democratic quality used here is comprised of an unweighted average of two Worldwide Governance Indicators: voice and accountability, and political stability[83]. These indicators are built upon multiple sources (e.g. household surveys and interviews with experts, firms, and non-governmental organisations), and are scaled between roughly -2.5 (poor democratic quality) and 2.5 (strong democratic quality). A threshold along this scale is of course normative, but we have chosen 0.80, as this is the approximate value for the United States and the United Kingdom—two democratic systems that are by no means the highest performing, but are nonetheless well-known in terms of their strengths and weaknesses.

3.10 Equality

Evidence for high-income countries suggests that more equal societies have fewer health and social problems than less equal ones[84]. We chose the Gini coefficient as our measure of equality, using equivalised (square root scale) household disposable income (i.e. after taxes and transfers). The data are from the October 2014 release (v5.0) of the *Standardized World Income Inequality Database*[85]. Given that the data are relatively sparse, particularly for recent years, we used data for 2005, the most recent year with data for a large number of countries. A maximum Gini coefficient of 0.30 was chosen as our threshold. To be consistent with our convention of a higher value on the social indicators representing better performance, we calculated equality as one minus the Gini coefficient (thus the threshold is a minimum of 0.70). The threshold value falls in between the Gini coefficients associated with "low" and "medium" total income inequality (0.26 and 0.36, respectively), as characterised by Piketty[86]. It also roughly corresponds to the level observed in the United States during the late-1970s.

3.11 Employment

A high level of employment is generally regarded as one of the most important indicators of national policy success. For an individual, employment enables social and economic autonomy[13], and has been shown to be a strong determinant of subjective well-being[87,88]. We measure employment as one minus the unemployment rate, where the latter refers to the share of the labour force that is without work but available for and seeking employment. To ensure comparability among countries, we use harmonised unemployment data from World Bank's *World Development Indicators*[73]. Some level of frictional unemployment is inevitable in any well-functioning economy, and is in fact desirable to allow workers to transition between jobs. This short-term unemployment differs from structural unemployment, where there is a mismatch between jobs and employee skills, or cyclical unemployment, which may occur due to a fall in the aggregate demand for goods and services [89]. We chose a threshold of 6% unemployment (i.e. 94% employment) as corresponding to full employment in our analysis. This level is roughly equivalent to the average non-accelerating inflation rate of unemployment (NAIRU) for OECD countries[90].

4 Rendering the "Safe and Just Space" Plots

Within Fig. 3 of the main text (and in the accompanying Supplementary Data), biophysical indicators are presented with respect to the per capita biophysical boundary, while social indicators are presented with respect to the social threshold. In each case this calculation involves dividing the indicator value by the given boundary or threshold. In the case of the biophysical indicators, which are on a ratio scale (i.e. they have an absolute zero), the value is calculated directly. However, some of the social indicators, such as democratic quality, are on an interval scale, and do not have an absolute zero. Others, such as nutrition, technically have an absolute zero, but it is questionable whether this zero value is meaningful.

For this reason, the social indicators are normalised such that the lowest value for a given indicator is assigned the value of zero, while the social threshold is assigned the value of one. This normalisation procedure preserves the social threshold as an absolute quantity (it is always one, regardless of the data), but allows the differences between countries to be visualised in the "safe and just space" plots. In mathematical terms, the normalised data are given by $y_{norm} = (y - y_{min}) \div (y^* - y_{min})$, where y is the social indicator, y^* is the social threshold, and y_{min} is the lowest value for the social indicator.

5 Data Gaps and Priorities for Future Work

Our analysis is inevitably limited by the data that are available. Future work to downscale planetary boundaries or apply the safe and just space framework may wish to consider the following issues:

- *Nitrogen and phosphorus data*. The nitrogen and phosphorus footprint data that we used are from the Eora MRIO database (http://worldmrio.com)[32,33] and while the input-output matrix contains data up to 2013, the footprints rely on fertilizer application rates for 1994–2001[34]. We scaled the data to match current estimates from Steffen et al.[24], but future work would benefit from incorporating newer data on biogeochemical flows into an MRIO model.

- *Blue water and international trade.* Although it is possible to measure water availability at the basin scale and in monthly intervals[42,43], we were unable to identify a consumption-based footprint indicator (i.e. one that fully accounts for trade) that could be meaningfully compared to a monthly boundary (and hence used the blue water footprint in comparison to a per capita share of the global boundary). Future work could explore alternative approaches.

- *Biodiversity.* The biosphere integrity boundary is particularly difficult to downscale. Although biodiversity footprint data do exist[91], they are not directly comparable to the biosphere integrity boundary put forward by Steffen et al.[24] HANPP may provide some indication of the aggregate pressure leading to biodiversity loss[92], but there would also be value in exploring biodiversity indicators more closely linked to the planetary boundaries framework.

- *Social thresholds*. The social indicators that we have used are based on Raworth's review of national submissions to the Rio+20 conference[17], and the thresholds for these indicators are based on values from the literature. It would be very interesting to repeat our analysis with different conceptualisations of a "good life", as well as social thresholds from participatory workshops.

- *Provisioning systems.* For us, the most important research priority moving forward is to open up the "black box" of physical and social provisioning systems. We hope that a better understanding of how different provisioning systems mediate the relationship between biophysical resource use and social outcomes will lead to new insights into how to reduce resource use while improving human well-being. We have recently begun to explore this question as part of a 5-year research project on "Living Well Within Limits" (https://lili.leeds.ac.uk).

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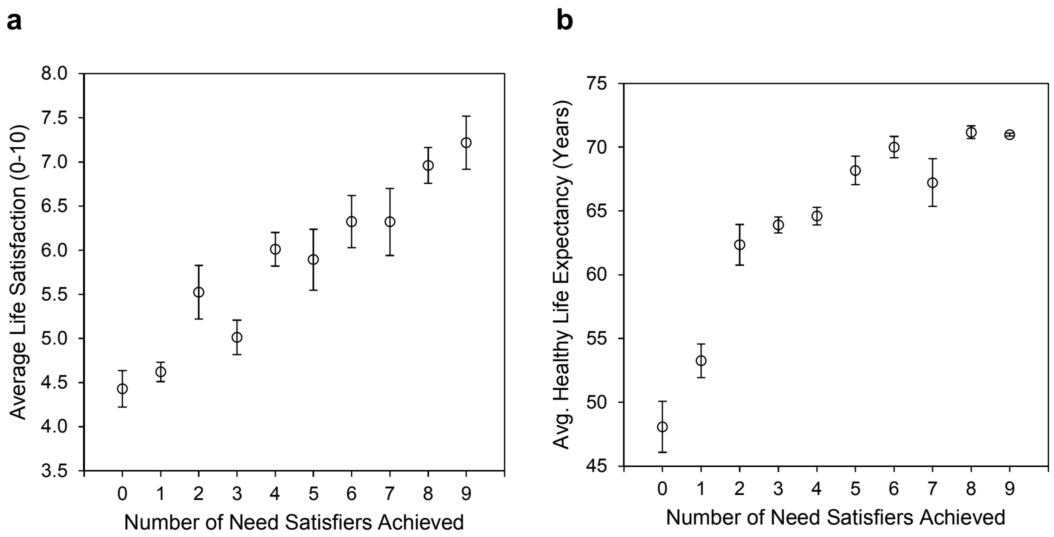
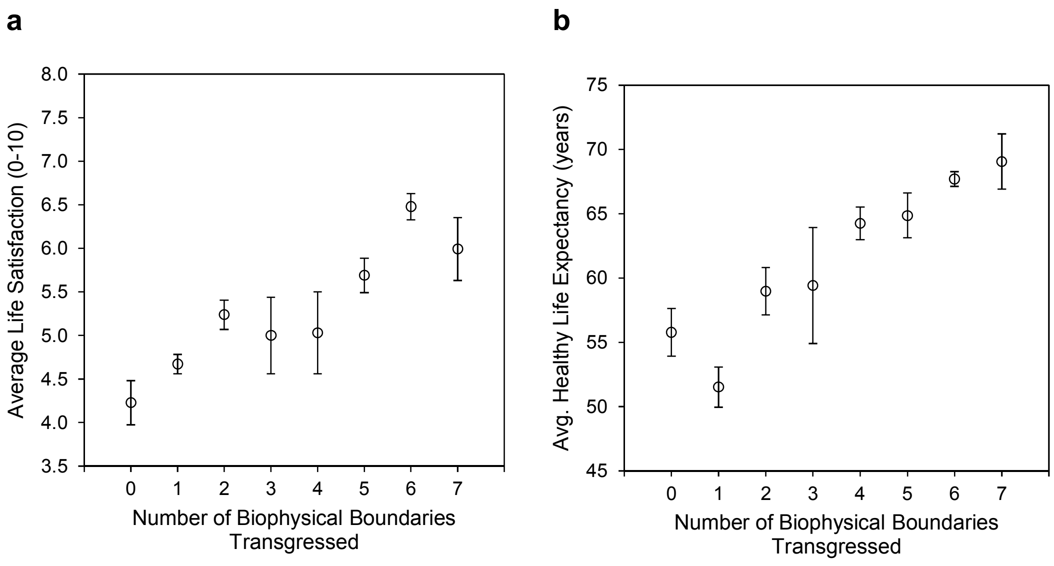
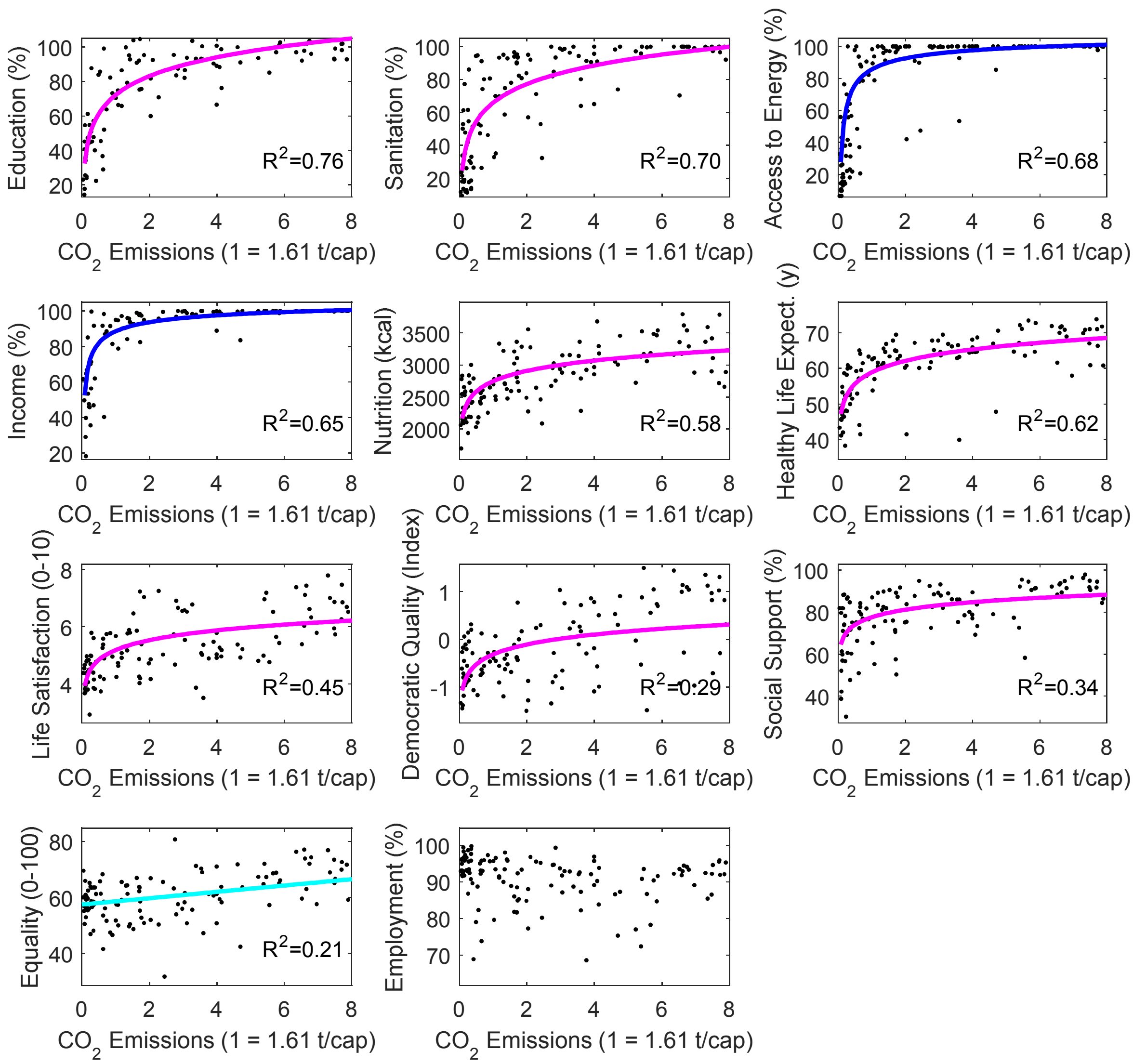
Supplementary Figures



Supplementary Fig. 1. Average values of (a) life satisfaction, and (b) healthy life expectancy, for countries based on the number of needs-related social thresholds achieved. Error bars give the standard error of the mean. The countries included are the same as in Fig. 2 of the main text (*N* = 109).



Supplementary Fig. 2. Average values of (a) life satisfaction, and (b) healthy life expectancy, for countries based on the number of biophysical thresholds transgressed. Error bars give the standard error of the mean. The countries included are the same as in Fig. 2 of the main text (*N* = 109).



Supplementary Fig. 3. The relationship between CO_2 emissions (scaled to the per capita biophysical boundary) and each of the social indicators. The best-fit curve (as determined by *AIC*), and the comparable R^2 value, are shown on each plot. Blue indicates a saturation curve, magenta indicates a linear–log curve, and cyan indicates a linear relationship. If no curve is shown, the relationship is not statistically significant.

Supplementary Tables

Supplementary Table 1. Data sources for the biophysical indicators used in the analysis

Indicator	Source	Description
CO_2 Emissions	Eora MRIO database[32,33]	Consumption-based allocation of CO_2 emissions from energy and cement production.
Phosphorus	Eora MRIO database[32,33,35]	Consumption-based allocation of phosphorus from applied fertilizer.
Nitrogen	Eora MRIO database[32,33,37]	Consumption-based allocation of nitrogen from applied fertilizer.
Blue Water	Water Footprint Network[44]	Consumption and pollution of blue water related to the domestic water supply, plus virtual-water imports, minus virtual-water exports.
eHANPP	Kastner et al.[47]	Consumption-based allocation of the human appropriation of net primary production (HANPP) embodied in final biomass products.
Ecological Footprint	Global Footprint Network[56]	Biologically productive land and sea area that is needed to produce the biotic resources that a country consumes, and to assimilate the CO_2 emissions it generates.
Material Footprint	Eora MRIO database[32,33,57]	Consumption-based allocation of used raw material extraction (minerals, fossil fuels, and biomass).

Supplementary Table 2. Data sources for the social indicators used in the analysis

Indicator	Source	Description
Life Satisfaction	World Happiness Report[64]	Response to the Gallup World Poll's Cantril life ladder question (0–10 scale).
Healthy Life Expectancy	World Happiness Report[64]	Number of years that an individual is expected to live in good health (without major debilitating disease or infirmity).
Nutrition	FAOSTAT[67]	Average calorific intake of food and drink per day, measured in kilocalories per capita.
Sanitation	World Bank[73]	Percentage of the population using improved sanitation facilities
Income	World Bank[73]	Percentage of the population living on more than $1.90 a day.
Access to Energy	World Bank[73]	Percentage of the population with access to electricity.
Education	World Bank[73]	Percentage enrolment in secondary school.
Social Support	World Happiness Report[64]	National average of responses to the question "If you were in trouble, do you have relatives or friends you can count on to help you whenever you need them, or not?"
Democratic Quality	World Happiness Report[64]	Average of two Worldwide Governance Indicators: voice and accountability, and political stability.
Equality	Standardized World Income Inequality Database[85]	Gini coefficient of household disposable income (i.e. after taxes and transfers).
Employment	World Bank[73]	Percentage of the labour force that is employed.

Supplementary Table 3. Strength of the relationship between biophysical and social indicators, as given by comparable R^2 of the best-fit curve

	CO_2 Emissions	Material Footprint	Phosphorus	Nitrogen	Ecological Footprint	Blue Water	eHANPP
Education	**.757 L** ***	**.664 L** ***	**.660 L** ***	**.613 L** ***	**.569 L** ***	*.314 S* ***	.041 p=.18
Sanitation	**.702 L** ***	**.594 L** ***	**.622 L** ***	**.595 L** ***	*.476 L* ***	*.361 L* ***	.113 p=.13
Access to Energy	**.684 S** ***	**.546 L** ***	**.572 L** ***	**.535 L** ***	*.435 L* ***	*.435 L* ***	
Income	**.650 S** ***	**.666 S** ***	**.549 L** ***	**.509 L** ***	*.498 L* ***	*.369 L* ***	
Nutrition	**.578 L** ***	**.532 L** ***	**.585 L** ***	**.552** ***	**.576 L** ***	*.227 L* ***	.002 p=.57
Healthy Life Expect.	**.617 L** ***	**.583 L** ***	**.609 L** ***	**.556 L** ***	*.456 S* ***	*.262 S* ***	.001 p=.70
Life Satisfaction	*.449 L* ***	**.516 L** ***	*.446 L* ***	*.384 L* ***	*.494 L* ***	.085 L ***	.071 L **
Democratic Quality	*.288 L* ***	*.441 L* ***	*.432 l* ***	*.449 l* ***	*.406 L* ***	.037 p=.03	.166 L ***
Social Support	*.342 L* ***	*.370 L* ***	*.288 L* ***	*.257 L* ***	*.435 S* ***	.081 L **	.097 L ***
Equality	*.213 l* ***	*.211 l* ***	*.210 l* ***	*.332 l* ***	.182 l ***	.040 p=.02	.021 p=.09
Employment	.008 p=.02	.010 p=.13	.013 p=.02	.023 S **	.015 p=.37	.041 S ***	.007 p=.11

Biophysical indicators are roughly ordered (from left to right) according to their ability to predict social performance. Social indicators are roughly ordered (from top to bottom) according to their association with resource use. Bold values indicate $R^2 \geq 0.5$; italics indicate $0.5 > R^2 \geq 0.2$. Letters indicate the shape of the best-fit curve: S = saturation, L = linear–logarithmic, and l = linear. *** indicates p < .001, ** indicates p < .01, while p ≥ .01 is not considered significant. All statistically significant relationships are positive (i.e. higher social performance is associated with higher resource use). See Supplementary Table 4 for *N*. No results are shown if the regression residuals are not normally distributed.

Supplementary Table 4. Number of data points *N* used in each regression

	CO_2 Emissions	Material Footprint	Phosphorus	Nitrogen	Ecological Footprint	Blue Water	eHANPP
Education	113	112	112	112	115	112	116
Sanitation	135	134	134	134	139	131	140
Access to Energy	145	144	144	144	149	141	150
Income	103	102	102	102	106	101	106
Nutrition	138	137	137	137	142	139	143
Healthy Life Expect.	131	130	130	130	133	127	134
Life Satisfaction	131	130	130	130	133	127	134
Democratic Quality	131	130	130	130	133	127	134
Social Support	130	129	129	129	132	127	133
Equality	128	127	127	127	133	129	133
Employment	145	144	144	144	149	141	150

Supplementary Table 5. Social goals included by different sources, organised to show the degree of similarity. Goals shown in brackets are proposed but not measured.

Raworth	Cole et al.	Dearing et al.	Sustainable Development Goals
Energy	Energy	Energy	Affordable and clean energy
Food security	Food security	Food security	Zero hunger
Income	Income	Income	No poverty
Water & sanitation	Water & sanitation	Water & sanitation	Clean water and sanitation
(Jobs)	Jobs	Jobs	Decent work and economic growth
Health care	Health care	Health care	Good health and well-being
Education	Education	Education	Quality education
(Voice)	(Voice)	(Voice)	Peace, justice, and strong institutions
Social equity		(Social equity)	Reduced inequalities
Gender equality		(Gender equality)	Gender equality
(Resilience)		(Resilience)	
	Housing		Sustainable cities and communities
	Household goods		
	Safety		
			Industry, innovation, infrastructure