Sustainability and human development: a proposal for a sustainability adjusted HDI (SHDI)

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1. Motivation

The ultimate aim of economic and social policy is to improve the lives of people, and to enhance their choices and capabilities. As stated by Mahbub ul Haq, founder of UNDP's Human Development Report, "The basic purpose of development is to enlarge people's choices. In principle, these choices can be infinite and can change over time. People often value achievements that do not show up at all, or not immediately, in income or growth figures: greater access to knowledge, better nutrition and health services, more secure livelihoods, security against crime and physical violence, satisfying leisure hours, political and cultural freedoms and sense of participation in community activities. The objective of development is to create an enabling environment for people to enjoy long, healthy and creative lives."

Conceptually, it is also clear that we need a broader notion of development based on more than on purely economic objectives but people centered. As stated by Amartya Sen "Human development, as an approach, is concerned with what I take to be the basic development idea: namely, advancing the richness of human life, rather than the richness of the economy in which human beings live, which is only a part of it."[2]

Measurement facilitates achieving human progress, and it has been an abiding interest of all Human Development Reports since 1990. Measuring human progress is a challenging task, however, fraught with a myriad of statistical and real world complexities. The first global Human Development Report in 1990 recognized the limitations of the existing measures of development. It presented the human development index (HDI) as an alternative to gross domestic product (GDP) in which people is put at the center. The HDI has since become a widely used measure of human progress more related to the lives of people.

The human development approach and the HDI are valid references for the consolidation of an alternative to GDP that integrates economic, social and environmental dimensions in a balanced manner. However, the tools currently available need to deliver an even more comprehensive measure

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[2] http://hdr.undp.org/en/humandev/

of human progress. This has been recognized by the Secretary-General, who stated in his message to the Global Human Development Forum on March 22-23, 2012 in Istanbul: "The concept of human development originated in well-founded dissatisfaction with using only gross domestic product as a measure of human progress. Though this understanding has become something of a benchmark in our thinking about development, there remains a need to dramatically change the way we value and measure progress."[3]

As part of a larger community of thinkers and actors working to improve the measurement of human progress, UNDP has contributed to global discussions to best measure economic and social progress. In recent years, these discussions have significantly expanded through the availability of new data and methodologies, including subjective measures of human well-being. The Organisation for Economic Cooperation and Development's Better Life Initiative is among the efforts to better capture what is important to people's lives. They have been significantly influenced by the Stiglitz-Sen-Fitoussi Commission, which concluded in 2009 that a broader range of indicators about well-being and social progress should be used alongside GDP. The Report of the United Nations Secretary-General's High-level Panel on Global Sustainability, also highlights that the international community should measure development beyond GDP, and it recommends the creation of a new index or set of indices that incorporate sustainability considerations. [4]A fuller picture of human development may require not only going beyond GDP but also adjusting the current HDI and the family of human development indices. The family of indices produced by the HDRO provides information on three different but interrelated aspects of human development: the average condition of people; levels of inequality (including gender issues); and levels of absolute deprivation. However, they do not take into account issues of unsustainable production and consumption patterns, among other factors that are important for enhancing human development.[5]

The evidence presented in the 2011 HDR suggests that, if no action is taken, the current and future environmental threats could jeopardize the extraordinary progress experienced in the HDI in recent decades.

Projection-scenarios exercises which followed the 2011 HDR[6] suggest that, in an "environmental challenge" scenario— that captures the adverse effects of global warming on agricultural production, on access to clean water and improved sanitation and on pollution— by 2050 the world HDI would be 8 percent lower than in the baseline (and 12 percent lower in South Asia and Sub-Saharan Africa). Moreover, under an even more adverse "environmental disaster" scenario —envisioning vast deforestation and land degradation, dramatic declines in biodiversity and accelerated extreme weather events— the global HDI would be at least 15 percent below the projected baseline. Consequently, if no

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[3] http://hdr.undp.org/en/humandev/forum2012/

[4] United Nations Secretary-General's High-level Panel on Global Sustainability (2012).

[5] From the HDI's inception, it was explicitly recognized that the concept of human development is larger than what can be measured by the index. This creates certain policy challenges, since there may be situations in which HDI progress masks deterioration in other key aspects. For example, political repression, crime and pollution could be on the rise at the same time that the HDI moves upward.

[6] See Hughes et. al. (2011).

measures are taken to halt or reverse current trends, the environmental disaster scenario leads to a turning point before 2050 in developing countries—their convergence with rich countries in HDI achievements begins to reverse.

These scenarios suggest that in many cases the most disadvantaged people bear and will continue to carry the repercussions of environmental deterioration, even if they contribute little to the problem. For example, low HDI countries have contributed the least to global climate change, but they have experienced the greatest loss in rainfall and the greatest increase in its variability, with implications for agricultural production and livelihoods.

The idea of this paper is to propose a sustainability-adjusted HDI (from now on SHDI) in which country's achievements in human development are penalized, to reflect the over-exploitation of the environment and its relative intensity.

2. What can we learn from trends in measures of sustainability?

a. Aggregate measures

There is an ongoing conceptual debate on how to define sustainability —mostly grouped either under weak sustainability or strong— which have implications for the measurement and assessment of sustainability trends. The main difference between both concepts of sustainability is that *weak* allows for substitutability across all forms of capital, while *strong* acknowledges that sustainability requires preserving so-called critical forms of natural capital (Neumayer, 2011). This conceptual debate also makes it difficult to have a broadly acceptable quantitative measure of sustainability. Here we review some of the aggregate measures that are most in use[7].

- *Green national accounting* is an approach that adjusts measures such as gross domestic product or savings for environmental degradation and resource depletion.[8] One important aggregate measure under this category is the World Bank's *Adjusted Net Savings* (ANS), also known as Genuine Savings, which takes the rate of savings, adds education spending and subtracts for the depletion of energy, minerals and forests as well as for damage from carbon dioxide emissions and pollution. Based on theory developed in Hamilton and Clemens (1999), the ANS aims to measure the change in present and future well-being, by showing the true rate of savings in an economy after taking into account how the economy invests and consumes all of its assets (human, natural and man-made)[9]. This measure is consistent with the weak sustainability framework, since it implies that the different kinds of capital are perfect substitutes, so that financial savings, for example, can replace a loss of natural resources or lower human capital.

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[7] For a comprehensive review of sustainability measures and indicators see Jha and Pereira (2011).

8 See the System of Environmental-Economic Accounts (SEEA) framework, which contains the internationally agreed standard concepts, definitions, classifications, accounting rules and tables for producing internationally comparable statistics on the environment and its relationship with the economy.

[9] The measure could be used as an indicator of future consumption possibilities. Ferreira, Hamilton and Vincent (2008) use a panel data for 64 countries (1970-82) and empirically show a significant positive correlation –after adjusting by population growth- between past per capita genuine savings and future changes in per capita consumption.

The Adjusted-Net Savings measure has been criticized by many authors like Neumayer (2004, 2010, 2011), mainly because of the human capital investment and the natural capital depreciation measures. The human capital investment (measure by current education expenditures) has been argued to be probably overestimated, because human capital is lost when individuals die. Also, health does not enter the calculus, which, according to Dasgupta (2007), makes the human capital notion used inadequate.

The depreciation of natural capital from extraction of natural resources is calculated as the price of the resource minus the average cost of extraction (as an approximation of the marginal cost) times the resource extraction volume. According to Neumayer (2010), there are preferable methods to compute the natural resource rents, like the one described in El Serafy (1981), which includes future capital gains when valuing the depreciation of exhaustible resources.[10] For example, valuing natural resources at market prices can overestimate the sustainability of an economy that produces them as the resources become scarcer and thus more expensive. Nonetheless, Hamilton and Ruta (2009) show that El Serafy approach is likely to lead to artificially low asset values and therefore low values for the depletion of the assets, resulting in an over-estimation of the social welfare (higher ANS).

The CO_2 emission damages are valued at $20 per metric ton of carbon in the ANS, following Frankhauser (1995). This, according to Dasgupta (2007) and others, is clearly an underestimate of the actual damage. The UNDP Human Development Report 2007-2008, for instance, considers that an adequate carbon price would be on the range US$60-100, and the Stern Report concludes that is above $100. As Frankhauser (1994) admits, the US$20 per metric ton of carbon value is only a rough order-of-magnitude assessment of the actual marginal costs of greenhouse gas emissions, and “care should be exercised when interpreting the figures”. Tol (2008) reviews a number of studies and shows that many of them find higher costs than Frankhauser (1995).

This is particularly problematic given the uncertainty embodied in greenhouse gas emissions and their monetary valuations. For instance, Garcia and Pineda (2011) using Tol (2008) meta-analysis showed that the number of countries considered unsustainable using adjusted net savings in 2005 would rise from 15 to 25 if we use a more comprehensive measure of emissions that includes methane and nitrous oxide as well as carbon dioxide and acknowledged monetary valuation uncertainties.

- *Composite indices* that aggregate social, economic and environmental indicators into a single index. Two examples under the strong sustainability framework are the *Ecological Footprint* (EFP)— a measure of the annual stress people put on the biosphere— and the *Environmental Performance Index*.

As Neumayer (2011) explains, the carbon emissions constitute the main element in the Ecological Footprint of many countries, and in fact there is a strong and statistically significant cross-country correlation (0.85) between the per capita volume of carbon emissions and the value of the EFP. Van den

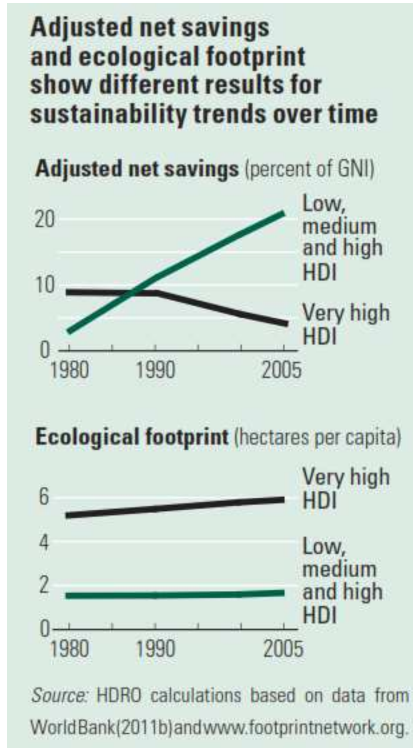
[10] Neumayer (2010) argues that this method is preferable to the one used by the World Bank, mainly because it does not depend on the assumption of efficient resource pricing; it takes into account the country’s reserves of natural resources, so that a given extraction volume has different implications for sustainability depending on the total stock available. For more detailed discussion see Teignier-Baqué (2010).

Berth and Verbruggen (1999), criticized the conversion of consumption categories into land area is incomplete and uses a set of weights which do not necessarily correspond to social weights because they do not reflect scarcity changes. Other problems, they argue, are that it denotes land area something that is hypothetical, since the world's EFP can exceed the world's total available productive land.[11]

From all of the aggregate measures of sustainability, only two are available for a large number of countries over a relatively long period of time: the World Bank's *Adjusted Net Savings* and the Global Footprint Network's *Ecological Footprint*.[12]

As we can see from the figure taken from the 2011 HDR, the Adjusted Net Savings measure is positive for all the groups according to the HDI, which means that the world is (weakly) sustainable. However, while the trend for low, medium and high HDI countries suggests that their sustainability (measured by this indicator) has improved over time that of the very high HDI countries is declining.

In contrast, the sustainability trend that emerges from the ecological footprint shows that the world is increasingly exceeding its global capacity to provide resources and absorb wastes. Given the calculations presented on the 2011 HDR, if everyone in the world had the same consumption level as people in very high HDI countries, with the current technologies, we would need more than three Earths to withstand the pressure on the environment. Current patterns of consumption and production are unsustainable at the global level and imbalanced regionally. And the situation is worsening, especially in very high HDI countries.



Source: HDRO calculations based on data from World Bank (2011b) and www.footprintnetwork.org.

b. Specific indicators

Patterns of carbon dioxide emissions over time constitute a good, although imperfect, proxy for the environmental impacts of a country's economic activity on climate. Evidence from the 2011 HDR

[11] According to Neumayer (2011) another important objection related to the energy or carbon footprint, which constitutes the main component of the EF for many countries, is that there are much less land-intensive ways of sequestering or avoiding carbon emission from burning fuels than (hypothetical) reforestation. For more detailed discussion see Teignier-Baqué (2010).

[12] Another more recent measure is the Environmental Performance Index, developed at Yale and Columbia Universities. The EPI measures environmental performance using a set of policy targets, which are based on international treaties and agreements, standard developed by international organizations and national governments, the scientific literature and expert opinion. This composite index uses 25 indicators to establish how close countries are to established environmental policy goals — a useful policy tool, built from a rich set of indicators and providing a broad definition of sustainability. But the measure's data intensity (requiring 25 indicators for more than 160 countries) inhibits construction of a time series so we will exclude it from the analysis of trends. Another important limitation of the EPI for international comparison is that some of its data is modeled.

showed that emissions per capita are much greater in very high HDI countries than in low, medium and high HDI countries combined. It also showed that there are significant differences across groups with different HDI achievements. Today, the average person in a very high HDI country accounts for more than four times the carbon dioxide emissions and about twice the emissions of the other important greenhouse gases (methane, nitrous oxide) as a person in a low, medium or high HDI country.

Results from the 2011 HDR also showed a strong positive association between the level of HDI (especially its income component) and carbon dioxide emissions per capita. This positive relationship was also found in terms of changes over time. Countries with faster HDI improvements also experience a faster increase in carbon dioxide emissions per capita. This hints at the fact that the recent progress in the HDI has been associated with higher emissions putting at risk its sustainability.[13]

Climate change —with effects on temperatures, precipitations, sea levels and vulnerability to natural disasters— is not the only environmental problem. Degraded land, forests and marine ecosystems pose chronic threats to well-being, while pollution has substantial costs that appear to rise and then fall with increasing levels of development.

The 2011 HDR showed that nearly 40 percent of global land is degraded due to soil erosion, reduced fertility and overgrazing. Between 1990 and 2010 Latin America and the Caribbean and Sub-Saharan Africa experienced the greatest forest losses, while desertification threatens the dry-lands that are home to about a third of the world's people. Some areas are particularly vulnerable—notably Sub-Saharan Africa.

b.i. Box: Carbon consumption and the "outsourcing" of emissions

The 2011 HDR showed that global carbon dioxide emissions have increased since 1970 — 248 percent in low, medium and high HDI countries and 42 percent in very high HDI countries. The global growth of 112 percent can be broken down into three drivers: population growth, rising consumption and carbon-intensive production. Rising consumption (as reflected by GDP growth) has been the main driver, accounting for 91 percent of the change in emissions, while population growth contributed 79 percent. The contribution of carbon intensity, in contrast, was a reduction of70 percent, reflecting technological advances. Hence, when added the individual contributions we are able to explain the 100 percent of the total growth, and results show to forces inducing more emission and only one force reducing it. In other words, the principal driver of increases in emissions is that more people are consuming more goods— even if production itself has become more efficient, on average. Although the carbon efficiency of production (units of carbon to produce a unit of GDP) has improved 40 percent, total carbon dioxide emissions continue to rise. Average carbon dioxide emissions per capita have grown 17 percent over 1970–2007.

[13] The discussion about the relationship between the environmental threats due to carbon dioxide emissions and achievements in human development should take into account a historical perspective, since the stock of carbon dioxide trapped in the atmosphere is a product of historical emissions. Today's concentrations are largely the accumulation of developed countries' past emissions. With about a sixth of the world's population, very high HDI countries emitted almost two-thirds (64 percent) of carbon dioxide emissions between 1850 and 2005, with the United States representing about 30 percent of total accumulated emissions.

Patterns of carbon dioxide emissions vary widely across regions and stages of development. While very high HDI countries account for the largest share of world carbon dioxide emissions, low, medium and high HDI countries account for more than three-fourths of the growth in carbon dioxide emissions since 1970. East Asia and the Pacific is the largest contributor by far to the increase in these emissions (45 percent), while Sub-Saharan Africa contributed only 3 percent, and Europe and Central Asia, 2 percent. We have data for a shorter period for methane and nitrous oxide, but in these cases too, the contribution of the East Asia and the Pacific region is pronounced. Trade enables countries to shift the carbon content of the goods they consume to the trading partners that produce them. Several countries that have committed to cutting their own emissions are net carbon importers, including Germany and Japan, as are countries that have not signed or ratified global treaties, such as the United States.

In a recent study Peters et. al. (2011) examined the “virtual carbon trade” flows, by defining a country’s carbon consumption as the difference between the tons of greenhouse gases it emits (“carbon production”) and the net carbon content of its imports and exports. Their estimates highlight a sizeable transfer of carbon from the poor world to the rich world”, so the authors argue that “the rich world has been ‘offshoring’ or ‘outsourcing’ its emissions” to developing countries.

However, divergences between the production and consumption of carbon cannot be ascribed solely to the “outsourcing” of carbon-intensive production from developed to developing economies. Relatively large carbon exports largely reflect countries’ natural resource endowments, rather than a “leakage” of carbon-intensive manufacturing away from developed economies. Furthermore, the virtual carbon trade data suggests that carbon- and energy-exporting countries are also more likely to permit domestic energy prices to lag behind world energy prices, in order to subsidize domestic energy consumption resulting in lower levels of energy efficiency.

Sources: Slay, Ben (2011), “Carbon consumption, transition and developing economies: Sinners, or sinned against?”, and HDRO 2011.

3. Incorporating sustainability into the measurement of human development

a. Existing alternatives

UNDP’s Human Development Index is one of the most prominent and known indicator of well-being. However, the HDI does not take into account sustainability variables in a broader sense. Recent academic work has mainly focused on examining the potential for ‘greening’ the HDI so as to include environmental and resource-consumption dimensions. These works have yielded various proposals for extending HDI to take sustainability and environmental aspects into account.

Shreyasi Jha (2009) proposed modifying the income dimension of the HDI which reflects the use of natural resources by using a more inclusive measure of wealth per capita, that includes natural capital. In this regard, the author proposes three viable alternatives: replace GDP with Net National Production; use World Bank’s Total Wealth indicator; or replace GDP with a measure for Green Net National Product.

De la Vega and Urrutia (2001), on the other hand, present a pollution-sensitive human development index. This indicator incorporates an environmental factor, measured in terms of CO_2 emissions from industrial processes per capita with the standard measure of human development. This composite measure penalizes the income component by taking into account the environmental costs arising from such output.

Morse (2003) proposes an environmentally sensible HDI, equal to the sum of the HDI plus the integral environmental indicator, which is the average of an indicator of the environmental state of country and an indicator of the environmental evaluation of human activities. The author emphasizes that any greening of the HDI should make sure that the basic HDI remains unmodified.

Constantini (2005) proposes to calculate a composite Sustainable Human Development Index as the simple average of the four development components: education attainment, social stability, sustainable access to resources (Green Net National Product), and environmental quality.

Other efforts include Dewan (2009) Sustainable Human Development (SHD) – in which the developmental goal is to achieve higher human development for the maximum number of people in present and future generations. Dahme et al. (1998)'s Sustainable Human Development Index -an extension for the HDI which is produced by using total material requirement- sums all material inputs (abiotic raw materials, biotic raw materials, moved soils, water and air) required to produce a country's national output. Ramanathan (1999)'s Environment Sensitive HDI -a product of HDI and Environment Endangerment Index (EEI)- is computed with data on deforestation, number of rare, endangered or threatened species, a greenhouse gas emissions index and a chlorofluorocarbon emissions index.

b. Sustainability Adjusted HDI (SHDI)

Neumayer (2004) stated that sustainability is the requirement to maintain the capacity to provide non-declining well-being over time. Sustainability, unlike well-being, is a future-oriented concept. Hence, he suggested that it is better to use separate indicators to trace these two concepts and not one. We understand this challenge, and we propose an approach for which indicators are calculated separately for each country, and later combined on our Sustainability Adjusted HDI. In the results section and in the Annex 2 we present tables and graphical analysis of the relationship between 6 sustainability indicators, 2 aggregate (ANS and EFP) and 4 specific indicators (per capita CO_2, per capita fresh water withdrawals, percentage of extinct species over total and percentage of land with permanent crops), and the HDI. This approach is in line with the one suggested by Neumayer (2010) and applied in the paper "Tracking humanity's progress towards sustainable development-combining HDI and Ecological Footprint" by the Swiss Foreign Minister Micheline Calmy-Rey's team to the UN High-Level Panel on Global Sustainability.

b.i. Linking present and future choices

Today, we are facing an increasing need for improvements in the measurement of human progress that would not only capture the scope of the choices available to the current generation but also the sustainability of these choices. In other words, we need a measure that is able to connect present choices to future choices. As was already mentioned, the basic purpose of development is to enlarge people's choices. However, as Anand and Sen (2000) explain, the basic idea of human development involves equal rights applied to all. Universalism considers unacceptable any form of discrimination based on class, gender, race, community, and also generation. This implies that future generations should receive the same kind of attention than the current generation.[14] This same idea can be found in the Human Development Report 1994: "There is no tension between human development and sustainable development. Both are based on the universalism of life claims".

Drawing upon the universalist principle, people should not only care about the choices that are open to them (as measured by the HDI), but also about how they were procured, and their impact on the choices available to future generations globally.

Thus, progress in human development achieved at the cost of the next generations should be viewed less favorably than progress achieved in a sustainable way. It is critical that this connection is fully integrated into the analysis and measurement of human progress. One of the main dimensions affecting the connection between the choices of current and future generations is the environment, but not the only one. For example, the savings and investment decisions of current generations will affect the possibilities for command over resources by the next generations; it is also well known that parents' education has a significant positive impact on the likelihood of their children being more educated, healthier, and with a future higher command over resources.[15] However, as we will see later in this paper, the existence of global sustainability thresholds and externalities (within and between generations), generates a particular relevance for environmental considerations when we explicitly connect present and future generation's choices.

b.ii. National and global sustainability, and the existence of tipping points

The previous analysis implies that inter-generational equity should be measured in a way that goes beyond national borders. When measuring progress at the country level, we should care about the potential negative effect of current generation's actions on the possibilities available to future generations globally.

For the analysis of sustainability it is crucial to distinguish between the local, national and global dimension. Measures of global sustainability examine the aggregate, although the effects of policies may vary greatly by location not only between countries but within countries as well. For example, as

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[14] A more utilitarian view can be found in Roemer (2009), who says that an ethically attractive approach to sustainability is one in which today we choose a consumption path that maximizes the level of the worst-off generation. The justification, he argues, is that since the birth date of a person is arbitrary, no generation should be better off than any other unless it comes without lowering the utility of the worst-off generation.

[15] Parents have an enormous influence on their children's education for several reasons, but most importantly because they are their children's first teachers (Gratz, 2006). They also affect children aspirations, since children with more highly educated parents developed higher aspirations for their own education and on average attained more education by age 19, which in turn related to higher levels of adult educational attainment Dubow *et al* (2009).

Dasgupta (2009) discusses, the world's poorest people often have no substitutes when their local resource base is degraded, so even if they live in a country considered sustainable, the conditions in which these disenfranchised groups live may not be. While recognizing that the local level is essential in the human development approach as well as for policy-making, the present analysis focuses on the global level owing to the pressing need to find a measurement tool that integrates both inter-generational and global equity. Most of existing aggregate measures of sustainability[16] typically lack of this kind of integrated framework; since they mostly focus on the country level, without taking into account the complexity of the global challenges that we are facing on this shared planet.[17]

Given the need of a general framework in which the concept of human development could be enhanced in a shared planet -not only today but tomorrow- we take a global perspective of sustainability, aiming to capture up to what extent our current life style is compromising future generations' human development. It is important also to clarify that our vision is not presented as necessarily contradictory with any other particular view of sustainability, but rather as an approach that is closer and more coherent with the human development paradigm.

The impact of a particular country to the global sustainability of the earth can be measured by taking into account the relative damage that the country's actions impose on the whole world, or, in other words by including the externalities of such country's action. Most existing approaches to sustainability, particularly those that use resource accounting such as the Adjusted Net Saving, have a country focus which does not allow them to internalize the global implications of countries' behavior.[18] The human development approach is a better guidance of what is important to sustain and how it should be sustained, by putting people at the center of the analysis now and in the future through the lens of the "universalist" principle.

There is an increasing consensus about the seriousness of the threats that humanity is facing in terms of global sustainability. As the Report of the United Nations Secretary-General's High-level Panel on Global Sustainability emphasized, awareness is growing on the fact that there is an increased danger of surpassing "tipping points" beyond which environmental changes accelerate, and become self-perpetuating, making it difficult or even impossible to reverse. The existence of these threats supports a vision of non-substitutability across all forms of capital, as the strong sustainability approach argues with respect to the role natural capital plays in absorbing pollution and providing direct utility in the form of environmental amenities.[19] They also support a vision in which a global perspective of sustainability is taken into consideration and not just the sustainability of individual countries in isolation.

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[16] As already discussed on section 2 of this paper.

[17] They also tend to focus only on adjusting economic or environmental indicators in ways that do not necessarily reflect non-linearities and tipping points, and which assume near-perfect substitutability of all types of capital or not substitutability at all.

[18] In fact, such an approach does not analyze the reasons why a particular country is depleting its assets, nor does it take into account that it is as important to sustain the stock of capital as how to (globally) sustain it. See Neumayer (2001, 2010).

[19] Sustainability proponents can be roughly divided, for analytical purposes, into those adhering more to a weak substitutability paradigm (assuming that natural and other forms of capital are essentially substitutable), and those

Our analysis aims for a greater integration of science into all levels of policymaking on sustainable development, as it has been the call from the Report of the United Nations Secretary-General's High-level Panel on Global Sustainability. The analysis of planetary boundaries developed by Rockström *et. al.* (2009)[20] is an important example of scientific work in this field. This approach argues that the anthropogenic pressures on the Earth System have reached a scale where abrupt global environmental changes can no longer be excluded. It proposes an approach to global sustainability based on definitions of planetary boundaries within which humanity can be expected to live safely. Transgressing one or more of these (nine) planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems. The Millennium Ecosystem Assessment and the Intergovernmental Panel on Climate Change (IPCC) are also important references that assess environmental challenges on human well-being based current knowledge, scientific literature, and data.

b.iii. The loss function

In our analysis, we use a pragmatic approach between a single composite indicator and a dash-board. Indicators of sustainability are calculated separately for each country and then integrated into a single indicator, but interpretation can be easily decomposed. The indicators to be used should preferably reflect the planetary boundaries that have been identified, which given the current scientific understanding, there are quantifications for seven of these: climate change; ocean acidification; stratospheric ozone; biogeochemical nitrogen cycle and phosphorus cycle; global freshwater use; land system change; and the rate at which biological diversity is lost [21] . Because of data limitations in terms of country coverage but also time coverage, there are only a few areas for which environmental indicators with implications for global sustainability can potentially be identified at the national level for a large number of countries over time, namely carbon dioxide emissions, land use for permanent crops and fresh water withdrawals. We aim at identifying those countries that are exceeding the "threshold" or planetary boundary needed to achieve sustainability.

The thresholds are taken from Rockström et. al. (2009), and Meinshausen et. al. (2009). For $C0_2$ total accumulated emissions over the next 50 years likely to keep temperature change within 2°C (886 gigatonnes a year gives a 8-37% probability of exceeding 2°C), global fresh water withdrawals of 4,000 cubic kilometers a year, which we expressed in per capita terms for our analysis, and land system change captured by a threshold of 15% of global ice-free land surface converted to cropland. Despite the considerable uncertainty and estimated variance around these thresholds in the scientific community, they are an important point of reference and it is important to do extensive sensitivity

adhering more to a strong sustainability paradigm (rejecting the notion of substitutability natural capital, or at least at least some parts thereof) (Neumayer, 2010).

[20] Rockström, J *et al* (2009). "Planetary Boundaries: Exploring the Safe Operating Space for Humanity." Ecology and Society 14(2).

[21] The two additional planetary boundaries for which they have not yet been able to determine a boundary level are chemical pollution and atmospheric aerosol loading.

analysis including as many indicators and incorporating the uncertainties around these thresholds as much as possible.[22]

The environmental variables included in the SHDI are not to be thought of as adding an extra dimension to the determination of societal well-being in a country. This point of view is in principle warranted by the very nature of the environmental variables under consideration: not those that affect the inhabitants of the country alone, but those that affect the planet as a whole.

Loss function: fair share and global responsibility

In order to guide policy action, it is of critical importance to combine the best available evidence provided by science with a sound concept of social justice. The issue of climate change has an important dimension of distributive justice. Nevertheless, since there is not a consensus on which is the most appropriate equity principle; it is necessary to specify the equity criteria to be applied. There is a wide variety of criteria that have been used in the climate change literature, such as egalitarianism –equal use right of the environment for every person-, sovereignty - equal use right of the environment at the level of nations-, ability to pay –proportionality of costs according economic well-being- and Rawl's maximin – the welfare of the worst-off country should be maximized-[23]. We follow a "Rights" approach by proposing a universally equal or "fair" use of the environment, in which everyone has the same right to use the planet's natural capital and the ecosystem services it generates, subject to constraints imposed by planetary boundary considerations.[24]

The way we incorporate this "Rights" approach is by a proper normalization of the indicators, looking for a combination in which resources are used both fairly and sustainably. We express our relevant sustainability indicators either in per capita terms (as it is the case for $C0_2$ emissions and fresh water withdrawals) or as a percentage of the country's land (as it is the case for land usage for permanent crops). We compare the per capita (or per land) use of the environment of a citizen in a country to the per capita (per land) threshold or maximum fair share according to the planetary boundary, in order to capture situations in which a country is having an excessive use of the environment by exceeding its fair share over the planetary boundaries. The important point to signal is that everyone has the right to achieve higher human development but within the limits imposed by the sustainability of our shared planet.

[22] We will present results for the lower bound and upper bound of the thresholds. The tighter threshold will be used for the baseline calculations, while the more relaxed will be presented as part of the sensitivity analysis in the annexes. The upper bound for CO_2 emissions is 1,437 gigatonnes accumulation for the next 50 with a 29-70% probability of exceeding 2°C. The upper bound for fresh water withdrawals is 6,000 cubic kilometers a year, while the upper bound for land system change of 20% of global ice-free land surface converted to cropland.

[23] For a more detailed discussion see Rose A and Kverndokk S. (2008), "Equity and justice in global warming".

[24] This point has also being made by authors like Raworth (2012): "Sustainability cannot be achieved without a necessary degree of equal fairness and justice. It appears therefore necessary to reconcile the social foundations of fairness with the planetary boundaries of a sustainable world".

It is also understood that even though each individual has the same right to a fair use of the environment, country level analysis requires an additional consideration for justice depending on the relative size of the country. We call this *global responsibility*, and we argue that the country's weight in regards to its behavior on the excessive use of the environment should be higher, the larger its population (or its territory, for the case of land usage). This concept of global responsibility increases with the size of the country with respect to the rest of the world. In this sense, it produces a balance between individual actions and a country's responsibility for the state of global sustainability.

If a country's population is exceeding its fair share of the planetary boundaries, its HDI is affected by a *loss function* which has two components: fair share and global responsibility, which captures the potential negative effect of current actions of a country on the possibilities available to future generations globally. To summarize, we propose a **Sustainability Adjusted HDI (SHDI)**, which imposes a loss function to a country's human development achievements given its degree of unfair use of the environment, according to the planetary boundaries. This is represented in equation 1, where we showed the SHDI for country *i*. See annex 1 for a description of the calibration and a mathematical representation of the SDHI.

$$\mathrm{SHDI^i} = \left(1 - \mathrm{G^i}\right) * \mathrm{HDI^i} \qquad (1)$$

Interpretation of SHDI

The standard interpretation of the HDI is that it is a capabilities index, thus intended to be a crude measure the size of the set of capabilities of the inhabitants in a country. The question is, then: what does it mean to applied a loss to the HDI of country *i* by $(1 - G_j^i)$? In other words: How is the SHDI given environmental indicator *j* and country *i,* $\mathrm{SHDI^i} = \mathrm{HDI^i} * (1 - G_j^i)$ to be interpreted?

Individuals in a country not only care about the multidimensional choices that are open to them (as measured by the HDI) but also about how those possibilities were procured and the impact that this will have on the choices of future generations. This implies that people care about inter-generational equity (which will now be captured by the SHDI). Thus, human development achievements at the cost of significantly contributing towards global environmental unsustainability (and then a significant reduction of the choices available to future generations) are viewed less favorably, by the citizens of that country, than those achieved under sustainability. Other things equal, a country that is within its fair share of planetary boundaries and not compromising the possibilities for future generations is viewed as having higher human development because it is a country whose citizens exhibit a higher degree of attention to inter-generational equity, and the prospects for future generations human development achievements globally.

4. Results

The following tables show a statistical description of the specific variables that we used for the calculation of the SHDI. For each one of them, we show the values for the set of countries in the HDI sample transgressing the planetary boundary (at the lower threshold), and a secondary threshold that is the value at the upper boundary in the level of uncertainty (less restricting).

As we can see, CO_2 emissions is the variable for which more countries transgress the lower threshold (59, in contrast with 49 for Freshwater withdrawals and 4 for Crop share of land area), which is consistent with the fact that this is one of the three planetary boundaries that according to Rockström et. al. (2009), humanity has already transgressed (along with biodiversity loss and the nitrogen cycle). This is also the reason why we see that the mean in the deviation for the countries that surpassed the threshold ("Intensity" columns) is higher in CO_2 emissions than in the other two variables (and with a higher standard deviation), which also translates in a bigger loss weight when adjusting the HDI ("Loss function" columns) for environmental sustainability.

stats	CO2 Emissions intensity		Freshwater Withdrawals intensity		Crop share intensity	
	above threshold (>4.29)	above threshold (>2.65)	above threshold (>885.43)	above threshold (>590.29)	above threshold (>20)	above threshold (>15)
mean	1.09	2.11	0.74	0.82	0.10	0.20
s.d	1.03	1.71	0.97	1.17	.	0.19
min	0.00	0.02	0.03	0.00	0.10	0.03
max	4.82	8.44	4.44	7.16	0.10	0.47
N (obs.)	51	59	21	49	1	4

stats	CO2 Emissions loss		Freshwater Withdrawals loss		Crop share loss	
	above threshold (>4.29)	above threshold (>2.65)	above threshold (>885.43)	above threshold (>590.29)	above threshold (>20)	above threshold (>15)
mean	0.008151	0.016862	0.003194	0.004259	0.000001	0.000208
s.d	0.022598	0.047166	0.007212	0.010847	.	0.000238
min	0.000024	0.000081	0.000012	0.000003	0.000001	0.000003
max	0.150304	0.273119	0.033541	0.073902	0.000001	0.000486
N (obs.)	51	59	21	49	1	4

Source: Own calculations**.**

Using this information, we were able to generate SHDI for a total of 118 countries for which we have the aggregated loss function as well as each of the individual sustainability indicators.

We created the SHDI combining all indicators as the simple average of the penalty from each of the indicators. The analysis shows that even though the correlation between the original HDI and the SHDI is very high (0.99), there are significant changes in ranking for some countries.

The effects of adjusting for sustainability using all indicators are higher for very high and high human development groups (as can be seen from the graph). At the lower boundary, there are 79 (out of 118) countries with at least one indicator above the planetary boundary (which implies a positive penalty). However, none of the countries exceeds the three thresholds at the same time.

There are 3 countries for which the penalty is higher than 5% (China (24.1%), the United States (17.4%), and the Russian Federation (7.38%)). The largest drop in ranking from our sample of 118 countries was 37 positions for the United States, 26 positions for China, and 17 positions for the Russian Federation. In the following table, we present the list of countries with losses in HDI ranking after adjusting for sustainability.

Countries positions lost with SHDI (at the lower boundary)

Country	HDI	SHDI	Loss	Rank HDI	Rank SHDI	Number of positions lost
United States	0.9099	0.7520	0.1735	4	41	-37
China	0.6871	0.5216	0.2410	65	91	-26
Russian Federation	0.7553	0.6996	0.0738	42	57	-15
Germany	0.9051	0.8770	0.0310	7	15	-8
Japan	0.9006	0.8776	0.0256	10	14	-4
Iran (Islamic Republic of)	0.7074	0.6962	0.0158	57	61	-4
Poland	0.8133	0.8038	0.0117	27	29	-2
Korea (Republic of)	0.8972	0.8787	0.0207	11	13	-2
Ukraine	0.7292	0.7243	0.0068	49	51	-2
Turkey	0.6991	0.6953	0.0055	60	62	-2
Pakistan	0.5043	0.4946	0.0192	93	95	-2
France	0.8844	0.8745	0.0111	15	16	-1
Canada	0.9081	0.8936	0.0160	6	7	-1
Netherlands	0.9099	0.9066	0.0037	3	4	-1
Saudi Arabia	0.7704	0.7614	0.0116	36	37	-1
Kazakhstan	0.7447	0.7384	0.0084	43	44	-1
South Africa	0.6194	0.6087	0.0173	78	79	-1

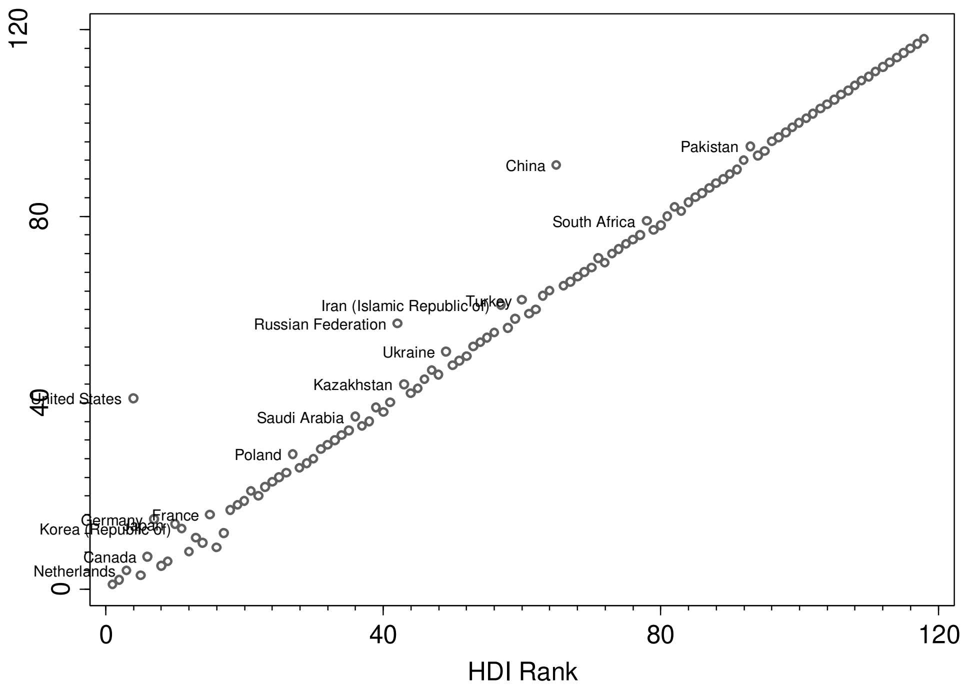
Source: Own calculations

Top rank positions lost with SHDI (at the upper boundary)

Country	HDI	SHDI	Loss	Rank HDI	Rank SHDI	Number of positions lost
United States	0.9099	0.8262	0.0919	4	25	21
Russian Federation	0.7553	0.7270	0.0375	42	49	7
Japan	0.9006	0.8807	0.0221	10	16	6
China	0.6871	0.6481	0.0568	65	70	5
Saudi Arabia	0.7704	0.7613	0.0118	36	38	2
South Africa	0.6194	0.6145	0.0079	78	80	2
Germany	0.9051	0.8919	0.0146	7	8	1
Iran (Islamic Republic of)	0.7074	0.7031	0.0062	57	58	1
Poland	0.8133	0.8092	0.0051	27	28	1
Ukraine	0.7292	0.7263	0.0041	49	50	1
Canada	0.9081	0.9006	0.0082	6	7	1
Netherlands	0.9099	0.9067	0.0035	3	4	1
Malaysia	0.7605	0.7581	0.0032	39	40	1

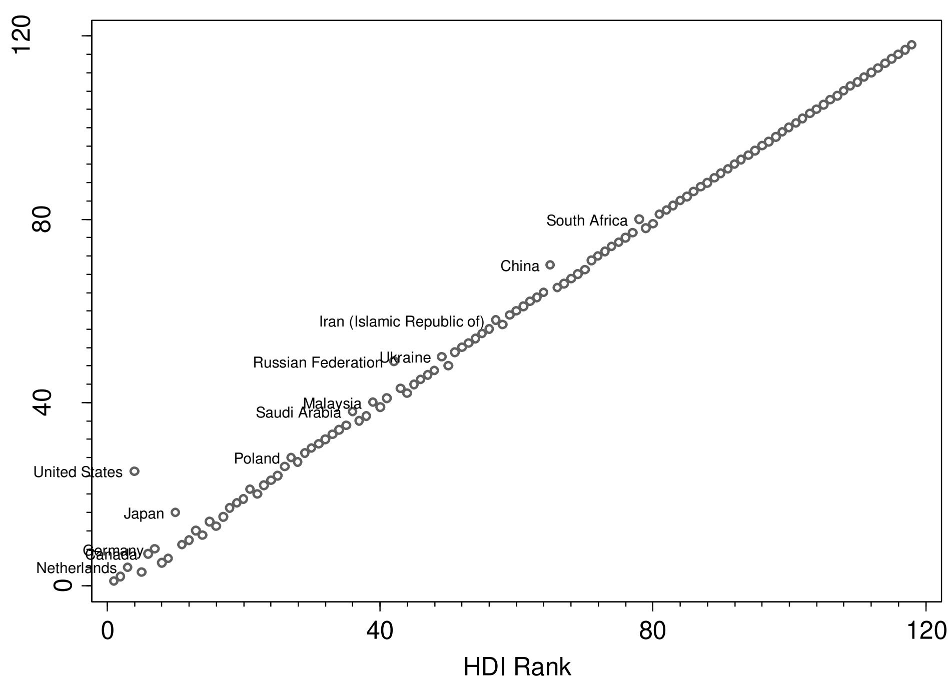
Source: Own calculations

Rank comparison between original HDI and SHDI (at the lower boundary)



Source: Own calculations

Rank comparison between original HDI and SHDI (at the upper boundary)



Source: Own calculations

5. Final remarks

The current challenges that human progress faces underscore the need to improve our measurement tools. We build upon this in a framework that combines the best available scientific evidence, a human centered development approach, and a social justice criterion in order to connect the choices available to current generations with those that could be available to future generations. The human development approach has been a powerful framework in the past for advancing the measurement of human progress. Today, this approach can help us make more explicit the profound connections between current and future generations' choices by offering a framework for understanding sustainability that connects inter- and intra-generational equity with global justice.

This analysis shows that there are important sustainability challenges ahead since there are 79 (out of 118) countries with at least one indicator above the planetary boundary (taking into account its more restrictive threshold). There are 17 countries that lost at least one position in the ranking after adjusting for sustainability. Between these countries, however, there are 3 countries for which the penalty is higher than 5% (China (24.1%), the United States (17.4%), and the Russian Federation (7.38%)). These countries experience the largest drop in ranking from our sample of 118 countries was 37 positions for the United States, 26 positions for China, and 17 positions for the Russian Federation.

Finally, the relevance of this proposal for a SHDI comes primarily from the fact that it does not try to add more dimensions to the HDI or to use monetary valuations to adjust one of its components (mainly income), which has important practical and conceptual limitations, since does not look at the broader set of capabilities that is captured by the HDI. This approach combines a series of sustainability indicators whose implications can be interpreted separately but that can also be aggregated in a way that gives a relevant perspective for a discussion of global sustainability. This approach is not necessarily contradictory with any other particular view of sustainability (in particular those discussed in this paper), but it is closer and more coherent with the human development approach.

There are significant data limitations in terms of frequency and availability, but the results clearly show important policy implications for understanding how to capture sustainability considerations when measuring human development. We particularly consider important the connection between present and future generations within a development framework that is people centered. We know that this is work in progress and further discussion, both conceptually and empirically (including intensive sensitivity analysis to different functional forms and alternative indicators), will help us to continue the constant search for improving our measures of human progress. So far we consider this to be the starting point of a larger research agenda, but we consider this to be a positive contribution to the broader discussion of sustainability from a human development perspective.

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Annex 1. Data, calibration and mathematical representation of the Sustainability Adjusted HDI (SHDI)

- *Data*

Carbon dioxide emissions per capita (2008), Annual freshwater withdrawals (2009) and Adjusted Net Savings (2010) are provided by the World Bank data query.[25] Land area and permanent crop area (2009) is found in FAO Stats.[26] The Ecological Footprint (2008) is found in the Global Footprint Network latest report (2011).[27] Data regarding extinct and assessed species by country is found in the International Union for Conservation of Nature (IUCN) "Red list".[28]

- *Mathematical representation of the Sustainability Adjusted HDI (SHDI)*[29]

The world has *K* countries. For simplicity countries are assigned a number from *1 to K*, so that *i=1,2, …, K*. Total world population is *N* individuals, where $N = \sum_1^K N_i$, and N_i is the population of country *i*. Therefore, $\{N_i\}_{i\in k}$ is the country's population. And let us call $\theta_i = \frac{N_i}{N}$.

For the environmental sustainability indicator *j*, $\{S_j^i\}_{i\in k}$, represents the level of use of the environment for indicator *j* in each country *i*. $\overline{s_j}$ corresponds to each individual in the planet's 'maximum fair share' according to the planetary boundary for indicator *j,* that is, the per capita equal share of the global planetary boundary, $\bar{S}_j$, where $\bar{S}_j = N * \overline{s_j}$.

We want to create a loss function with respect to the environmental sustainability indicator (or a combination of them). Therefore, let us start with a general definition of what the loss function should comprise.

Definition: *A loss function,* $G_j^i: \langle \{\overline{s_j}, \bar{S}_j\}, \{N_i\}_{i\in k}, \{S_j^i\}_{i\in k}, \{\theta_i\}_{i\in k} \rangle \to [0,1]_{i\in k}$ *such that each component of G is weakly increasing in* S_i.

This function has three important features:

1. *It depends on the whole world situation, and gives a particular value for each country.*
2. *It is bounded between 0 and 1, for each country.*
3. *When the pollution of a country increases, all other things equal, the penalty for such a country cannot decrease.*

Now we want some other properties, in order to obtain our desired loss function. With these properties, we specify which countries are going to be positively penalized:

[25] http://databank.worldbank.org/ddp/home.do
[26] http://faostat3.fao.org/home/index.html#DOWNLOAD
[27] http://www.footprintnetwork.org/en/index.php/GFN/page/footprint_data_and_results/
[28] http://www.iucnredlist.org/about/summary-statistics
[29] This section uses many inputs from Zambrano (2012) and Herrero (2012).

P1. **No penalty for good behavior.** *A country that pollutes less than its share minimum fare gets no penalty: If* $S_j^i \leq \theta_i \overline{s}_J$ *then,* $G_j^i \left[\langle \{\overline{s}_J, \bar{S}_j\}, \{N_i\}_{i\epsilon k}, \{S_j^i\}_{i\epsilon k}, \{\theta_i\}_{i\epsilon k} \rangle \right] = 0.$

We can call this the *exclusion* property. Together with the wealth increasingness it implies that all countries polluting below their minimum fair share receive no penalty.

P2. **Full penalty for full pollution.** *A country that in isolation exceeds the maximum boundary receives full penalty: If* $S_j^i \geq \bar{S}_j$, *then* $G_i^j \left[\langle \{\overline{s}_J, \bar{S}_j\}, \{N_i\}_{i\epsilon k}, \{S_j^i\}_{i\epsilon k}, \{\theta_i\}_{i\epsilon k} \rangle \right] = 1.$

This property is similar to the *exhaustion* property in Herrero and Villar (2001). For countries exceeding the global planetary boundary -and given weak monotonicity- all countries above that level receive full penalty.

P3. **Constant penalty trade-offs.** *If two countries, i and j, keeping their emissions in the intervals* $[\theta_i \overline{s}_J, \bar{S}_j]$, $[\theta_j \overline{s}_J, \bar{S}_j]$ *respectively, increment their emissions in the same amount, the relative value of their penalties is constant (independent of the common amount they increase). That is, if* $s_i^2 - s_i^1 = s_j^2 - s_j^1$, *then* $\frac{G_j^2 - G_j^1}{G_i^2 - G_i^1} = k(i,j)$.

This property has been called "Direct Capability", meaning that a country that diminishes (or improves) the environmental variable by an amount of, say "D" when polluting beyond its "fair share", diminishes (improves) its capabilities in direct proportion to "D". P3 is an extension to that principle, but applied to two countries, making explicit a sort of fair treatment in the relationship between the behavior of the penalties for different countries

Theorem: *A penalty function satisfies P1. P2 and P3 iff*

$$G_i^j \left[\langle \{\overline{s}_J, \bar{S}_j\}, \{N_i\}_{i\epsilon k}, \{S_j^i\}_{i\epsilon k}, \{\theta_i\}_{i\epsilon k} \rangle \right] = \max\left\{0, min\left\{1, \left[\frac{\left[S_j^i - \theta_i \overline{S}_J\right]_+}{\bar{S}_J - \theta_i \overline{S}_J}\right]\right\}\right\}$$

$$= \max\left\{0, min\left\{1, \left[\frac{\left[s_j^i - \overline{s}_J\right]_+}{\overline{s}_J}\left(\frac{N_i}{N - N_i}\right)\right]\right\}\right\}$$

Therefore, we could also represent the loss function G_j^i for indicator *j* and country *i*, as the following:

$$G_j^i \left[\langle \overline{s}_J, \{\beta_j^i\}_{i\epsilon k}, \{s_j^i\}_{i\epsilon k} \rangle \right] = min\left\{1, \beta_\mathrm{j}^\mathrm{i} * \frac{\left[s_j^i - \overline{s}_J\right]_+}{\overline{s}_J}\right\}$$

Given that

$$= \frac{\left[S_j^i - \theta_i \bar{S}_J\right]_+}{\bar{S}_J - \theta_i \bar{S}_J} = \frac{\left[S_j^i - \frac{N_i \bar{S}_J}{N}\right]_+}{\bar{S}_J - \frac{N_i \bar{S}_J}{N}} = \frac{\left[S_j^i - \frac{N_i \bar{S}_J}{N}\right]_+}{\bar{S}_J \left(1 - \frac{N_i}{N}\right)} = \frac{\left[S_j^i - \frac{N_i \bar{S}_J}{N}\right]_+}{\bar{S}_J}\left(\frac{N}{N - N_i}\right)\left(\frac{N_i}{N_i}\right) = \frac{\left[S_j^i - \frac{N_i \bar{S}_J}{N}\right]_+}{\bar{S}_J}\left(\frac{N_i}{N - N_i}\right)\left(\frac{N}{N_i}\right)$$

$$= \frac{\left[\frac{S_j^i}{N_i} - \frac{N_i \bar{S}_J}{N N_i}\right]_+}{\frac{\bar{S}_J}{N}}\left(\frac{N_i}{N - N_i}\right) = \frac{\left[\frac{S_j^i}{N_i} - \frac{\bar{S}_J}{N}\right]_+}{\frac{\bar{S}_J}{N}}\left(\frac{N_i}{N - N_i}\right) = \frac{\left[s_j^i - \bar{s}_J\right]_+}{\bar{s}_J}\left(\frac{N_i}{N - N_i}\right)$$

So, $\beta_{\mathrm{j}}^{\mathrm{i}} = \left(\frac{N_i}{N-N_i}\right)$.

where *c* refers to carbon dioxide emissions per capita, *w* refers to fresh water withdrawals and l refers to permanent crop share of land area, so *j=c,w,l*; and, the operation $[\quad]_+$ is defined as $[x]_+ = max\{x, 0\}$.

The term $\frac{\left[s_j^i - \bar{s}_J\right]_+}{\bar{s}_J}$ measures the degree or intensity of "unfair" or "excessive" use of the environment of the average citizen in each country *i* (as a proportion of the *per capita* threshold or maximum fair share). While β_j^i measures the weight given to the average unfair use by country *i* of the environment (measure by indicator *j*).

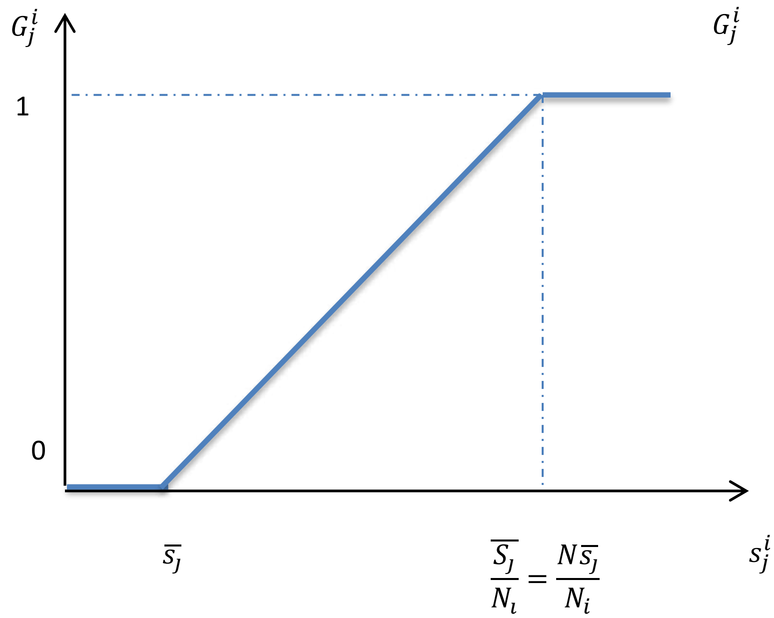
So, G_j^i is the overall loss function that is imposed to country *i*'s human development achievements given its degree of unfair use of the environment, according to the global planetary boundary for environmental indicator *j*.

G_j^i is intended to be the answer to the following question: Imagine a country A, with perfect achievements in health, education, and income (thus having an HDI of "1"), and that it is between the global environmental boundaries (thus also having an SHDI of "1"). Compare this to country B, also with perfect achievements in health, education, and income but with a level of, say, its per capita CO_2 emissions are exactly twice the level of per capita maximum fair share. Country B will also have an HDI of "1" but an SHDI of (1*(1- G_c^i)). This is similar for any other indicator on *j*.

The existing research on the planetary boundaries and the available data, we are able to have measures of the fair or unfair use of the global environment.

The intuition for the value of β_j^i is that we can argue the case so that when a country, say country *i*, alone hits the planetary boundary, this will impose unacceptable negative effects on the available choices of future generations and thus in this case the country receives the maximum loss and therefore $G_j^i = 1$. This will create two discontinuities on the loss function for country *i* on environmental dimension *j*. The first one is that its value is 0 if the country's per capita use of the environment is lower than the fair per capita share (P1. No penalty for good behavior); and the second one is that it has a value of 1 if country's per capita use of the environment is such that it hits or exceeds the planetary boundary (P2. Full penalty for full pollution). The intuition could be enhanced by the following Figure.

Figure 1. Graphical representation of the loss function G_j^i



We can therefore give a nice interpretation of the two components of G_j^i:

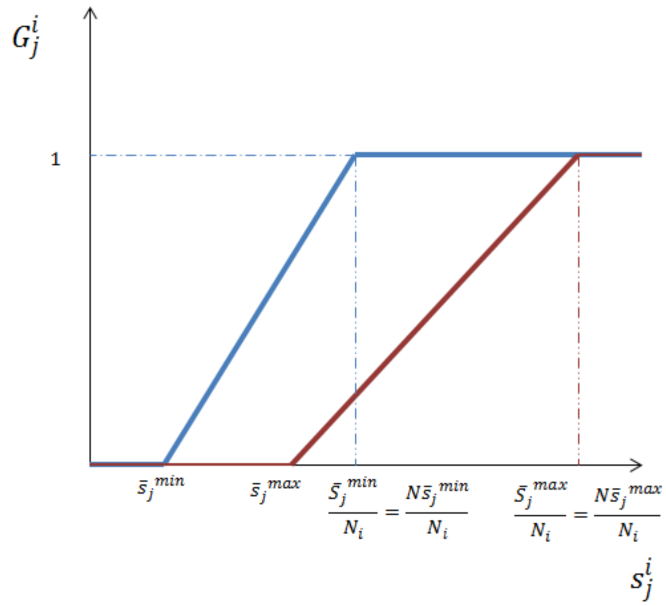
We call $\frac{\left[s_j^i - \bar{s}_J\right]_+}{\bar{s}_J}$ the *fair share of the environment* term, given that this is an expression that compares the per capita use of the environment of a citizen in country *i* to the per capita threshold or maximum fair share according to the planetary boundary. This terms capture when a country is having an *excessive* use of the environment by exceeding its fair share.

We call $\frac{N_i}{N-N_i}$ the *global responsibility* term, given that this is an expression that gives higher weight to excessive use of the environment behavior, the larger is the population of the country. In other words, the larger a country is with respect to the rest of the world, the larger is its responsibility for the use of the environment from its average citizen. Note that this representation is also valid for the case of land usage, since the fair share term is calculated for each country as the same proportion as the global threshold, and the global responsibility term now uses the country's area (instead of its population) as the weighting mechanism.

Including levels of uncertainty in the loss function

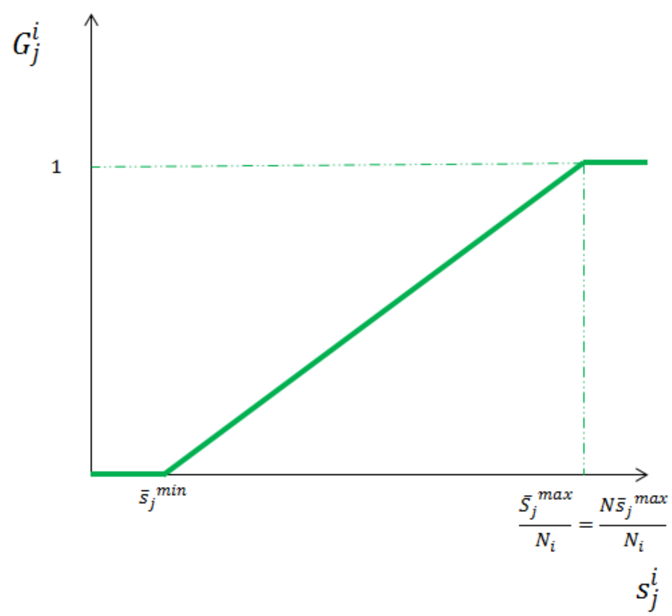
Since the planetary boundaries are intrinsically uncertain values, we use the confidence interval that Rockstrom *et al* (2009) use in their estimations. Therefore, our Figure 1, under two possible thresholds becomes:

Figure 2. Graphical representation of the loss function G_j^i with a minimum and a maximum planetary boundary



An interesting possibility is to define our loss function as to include the minimum per capita fair share and the maximum global planetary boundary. The graph would therefore become:

Figure 3. Graphical representation of the loss function G_j^i with the minimum per capita fair share and the maximum global planetary boundary



In this case, the loss function would be defined as:

$$G_i\left[\langle\{s^{min}, S^{max}\}, \{w_i\}_{i\epsilon N}, \{s_i\}_{i\in N}, \{\theta_{i_i}\}_{i\in N}\rangle\right]$$

And the same former three properties would apply.

The loss function would look like this:

$$G_i\left[\langle\{s^{min}, S^{max}\}, \{w_i\}_{i\epsilon N}, \{s_i\}_{i\in N}, \{\theta_{i_i}\}_{i\in N}\rangle\right] = min\left\{1, \left[\frac{[s_i - \theta_i S^{max}] +}{S^{max} - \theta_i s^{min}}\right]\right\}$$

From this, we can derive the *global responsibility* term, by setting G_j^i equal to 1. Therefore, when country's *i* per capita consumption hits the planetary threshold, so for this country $s_j^i = \frac{\overline{\bar{S}_j^{max}}}{N_\iota} = \frac{N\bar{S}_j^{max}}{N_i}$.Given this, we can define β_j^i as follow:

$$1 = \beta_j^i * \frac{\left[\frac{\bar{S}_j^{max}}{N_i} - \bar{s}_j^{min}\right]_+}{\bar{s}_j^{min}}$$

We can think that the maximum threshold is a value proportional to the minimum:

$\bar{S}_j^{max} = \alpha_j \bar{S}_j^{min}$, so that $\alpha_j = \frac{\bar{S}_j^{max}}{\bar{S}_j^{min}}$

In which $\alpha_j > 1$

Therefore,

$$1 = \beta_j^i * \frac{\left[\frac{\alpha_j \overline{S}_j^{min}}{N_i} - \overline{s}_j^{min}\right]_+}{\overline{s}_j^{min}}$$

So,

$$1 = \beta_j^i * \frac{\overline{s}_j^{min}\left[\alpha_j N - N_i\right]_+}{\overline{s}_j^{min} N_i}$$

$$\beta_{ji} = \frac{N_i}{\alpha_j N - N_i}$$

Calculation of SHDI

We can adjust the HDI by using the loss function $\mathrm{G}_{\mathrm{j}}^{\mathrm{i}}$ for indicator *j* and country *i*:

$$\mathrm{SHDI}_{\mathrm{j}}^{\mathrm{i}} = \left(1 - \mathrm{G}_{\mathrm{j}}^{\mathrm{i}}\right) * \mathrm{HDI}^{\mathrm{i}}$$

Giving equal weights to each sustainability indicator, we can represent the penalty function G^{i} for country *i* as the simple average of all penalties from each indicator for which the country is exceeding its fair share:

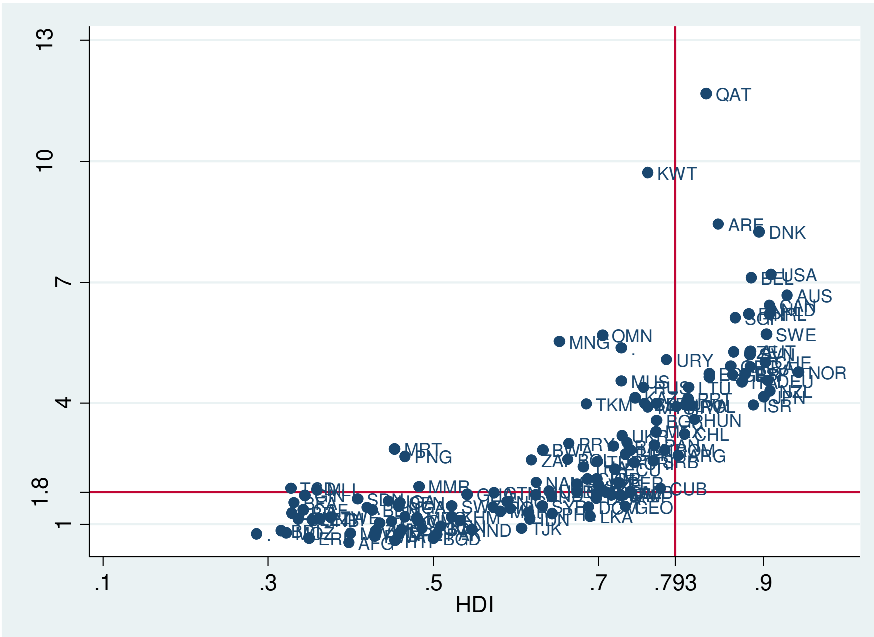
$$\mathrm{G}^{\mathrm{i}} = \left(\frac{1}{3}\right) * \mathrm{G}_{\mathrm{emissions}}^{\mathrm{i}} + \left(\frac{1}{3}\right) * \mathrm{G}_{\mathrm{water}}^{\mathrm{i}} + \left(\frac{1}{3}\right) * \mathrm{G}_{\mathrm{land}}^{\mathrm{i}}$$

With this loss, we adjust the HDI for country *i*:

$$\mathrm{SHDI}^{\mathrm{i}} = \left(1 - \mathrm{G}^{\mathrm{i}}\right) * \mathrm{HDI}^{\mathrm{i}}$$

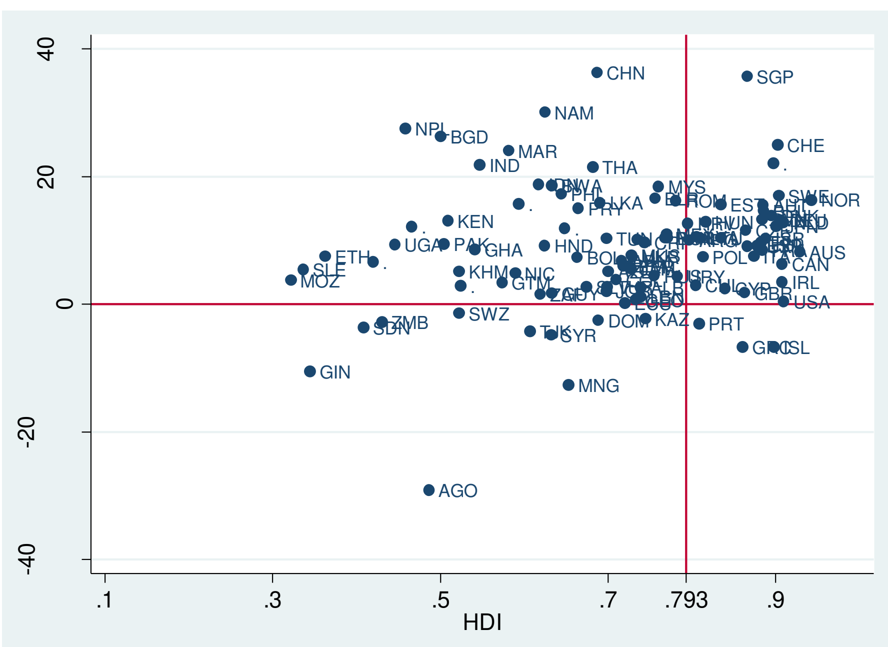
Annex 2. Relationship between sustainability indicators and the Human Development Index

Figure 1: Human Development Index and Ecological Footprint (2008)



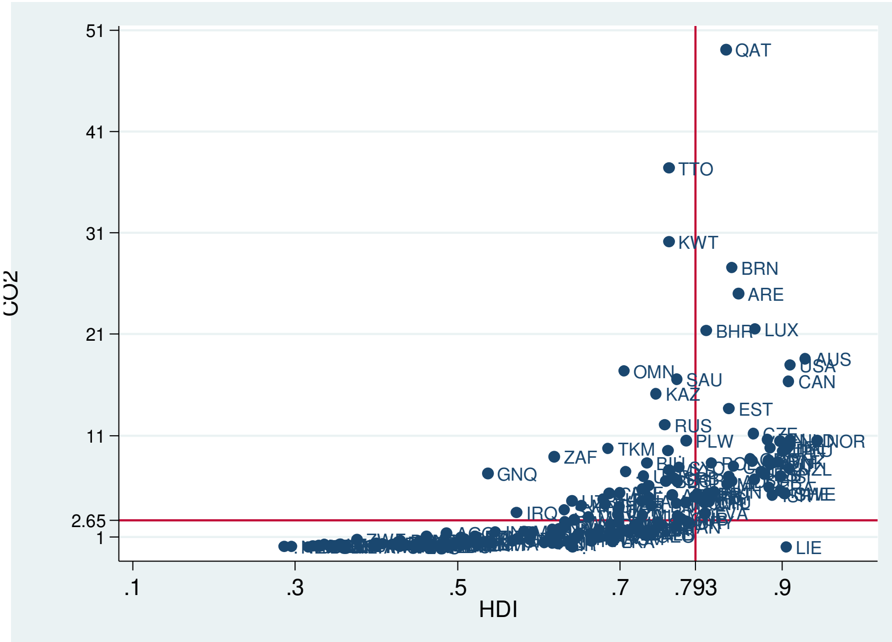
Sources: UNDP and Global Footprint Network (2011).

Figure 2: Human Development Index and Adjusted Net Savings (2010)



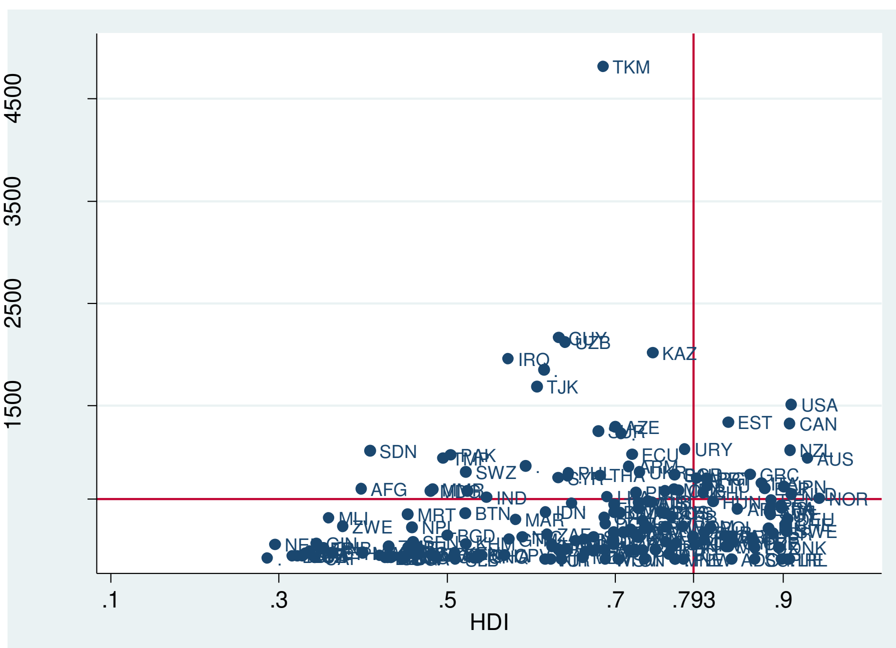
Sources: UNDP and World Bank.

Figure 3: Human Development Index and CO_2 emissions per capita (2008)



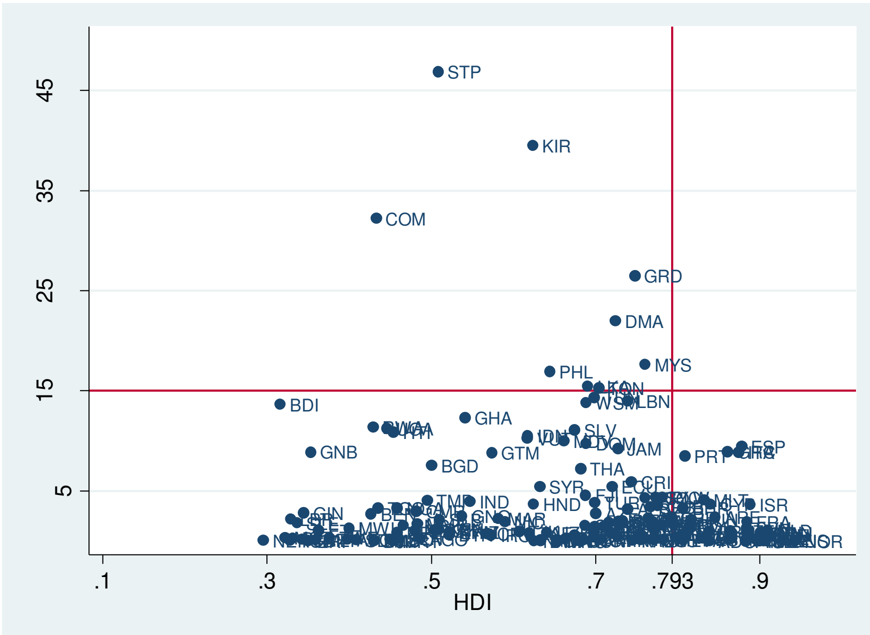
Sources: UNDP and World Bank.

Figure 4: Human Development Index and fresh water withdrawals per capita (2009)



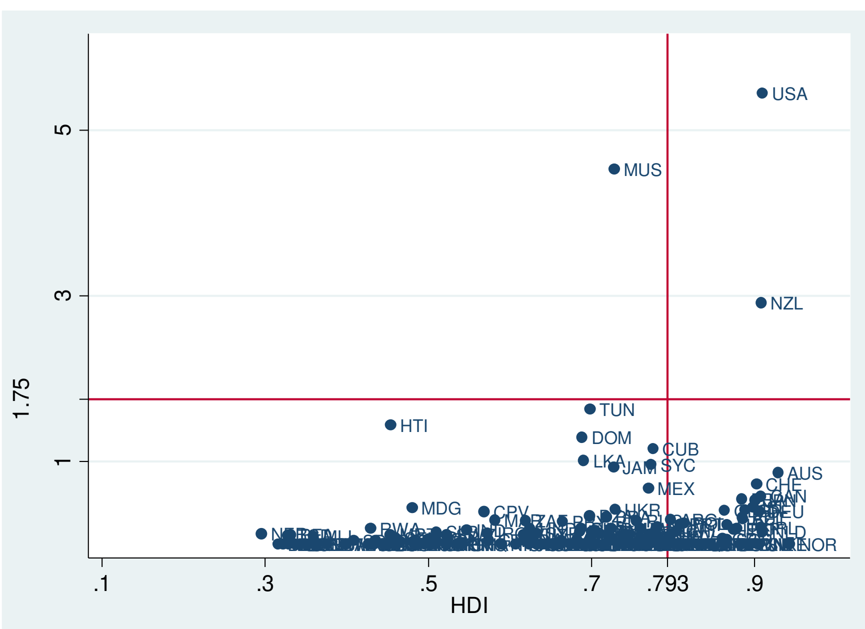
Sources: UNDP and World Bank.

Figure 5: Human Development Index and share of land with permanent crops (2009)



Sources: UNDP and FAO.

Figure 6: Human Development Index and species extinct as percentage of total species (2010)



Sources: UNDP and the IUCN “Red list”.

The table below is similar to the one presented on section 4, which shows a statistical description of the relevant variables. For each one of them, we show the values for the whole set of countries in the HDI sample (column "All") and in its left side, the values for the subset of countries transgressing the planetary boundary (at the lower threshold). In the case of the Ecological Footprint (EFP) the threshold is 1.8, and for the Adjusted Net Savings (ANS) the threshold value is 0, and for the share of extinct species over total we use one standard deviation above the mean.

stats	EFP		ANS		CO2		Freshwater		Cropshare		extshare	
	above threshold (>1.8)	All	below threshold (<0)	All	above threshold (>2.65)	All	above threshold (>590.29)	All	above threshold (>15)	All	above threshold (>1.75)	All
mean	4.10	2.90	-6.98	8.64	9.13	4.82	1077.16	613.84	25.10	4.02	4.79	0.25
s.d	1.91	2.05	7.44	9.60	7.55	6.70	691.74	604.78	10.44	6.82	1.43	0.75
min	1.80	0.54	-29.16	-29.16	2.69	0.02	592.54	13.90	15.28	0.00	2.92	0.00
max	11.68	11.68	-1.43	36.26	49.05	49.05	4818.18	4818.18	46.88	46.88	6.25	6.25
N (obs.)	82	140	13	104	90	187	49	118	11	186	4	186

Source: Own calculations.

As we can see from the figures, the only two indicators with a strong positive and statistically significant correlation with HDI are EFP and CO_2 emissions per capita (.75 and .55, respectively). These indicators have the largest share of countries above the threshold, while the share of extinct species over total has the lowest. In fact, their figures looks very similar when we just represent the common sample of countries for which both indicators exist.

Figure 7: Human Development Index, CO_2 emissions per capita and Ecological Footprint (2008)

(Common sample, 140 countries)

Sources: UNDP, World Bank and Global Footprint Network (2011).

Annex 3. Changes in rank of the top 10 and bottom 10 countries according to the HDI and SHDI ranks

The following tables present the top 10 countries (out of 118) according to the HDI rank and SHDI as well as the change in rankings due to the adjustment from unsustainable environmental behavior. As the tables shown, most of the changes in rankings occur at the upper portion of the distribution, while fewer changes occur at the lower part of it. This result is just consistent with the fact that relatively low human development countries contribute very little to the global environmental unsustainability.

Changes in rank of the top 10 countries after adjusting for sustainability (lower bound):

Country	HDI	SHDI	Loss	Rank HDI	Rank SHDI	Change in rank
Norway	0.9430	0.9420	0.0011	1	1	0
Australia	0.9289	0.9187	0.0110	2	2	0
Netherlands	0.9099	0.9066	0.0037	3	4	-1
United States	0.9099	0.7520	0.1735	4	41	-37
New Zealand	0.9084	0.9076	0.0009	5	3	2
Canada	0.9081	0.8936	0.0160	6	7	-1
Germany	0.9051	0.8770	0.0310	7	15	-8
Sweden	0.9038	0.9026	0.0014	8	5	3
Switzerland	0.9025	0.9015	0.0011	9	6	3
Japan	0.9006	0.8776	0.0256	10	14	-4

Changes in rank of the top 10 countries after adjusting for sustainability (upper bound):

Country	HDI	SHDI	Loss	Rank HDI	Rank SHDI	Change in rank
Norway	0.9430	0.9420	0.0010	1	1	0
Australia	0.9289	0.9236	0.0056	2	2	0
Netherlands	0.9099	0.9067	0.0035	3	4	-1
United States	0.9099	0.8262	0.0919	4	25	-21
New Zealand	0.9084	0.9081	0.0003	5	3	2
Canada	0.9081	0.9006	0.0082	6	7	-1
Germany	0.9051	0.8919	0.0146	7	8	-1
Sweden	0.9038	0.9035	0.0003	8	5	3
Switzerland	0.9025	0.9023	0.0003	9	6	3
Japan	0.9006	0.8807	0.0221	10	16	-6

Source: Own calculations

Top 10 countries for HDI and SHDI:

Country	Rank HDI	Country	Rank SHDI (lower bound)	Country	Rank SHDI (upper bound)
Norway	1	Norway	1	Norway	1
Australia	2	Australia	2	Australia	2
Netherlands	3	New Zealand	3	New Zealand	3
United States	4	Netherlands	4	Netherlands	4
New Zealand	5	Sweden	5	Sweden	5
Canada	6	Switzerland	6	Switzerland	6
Germany	7	Canada	7	Canada	7
Sweden	8	Israel	8	Germany	8
Switzerland	9	Slovenia	9	Korea (Republic of)	9
Japan	10	Austria	10	Israel	10

Source: Own calculations

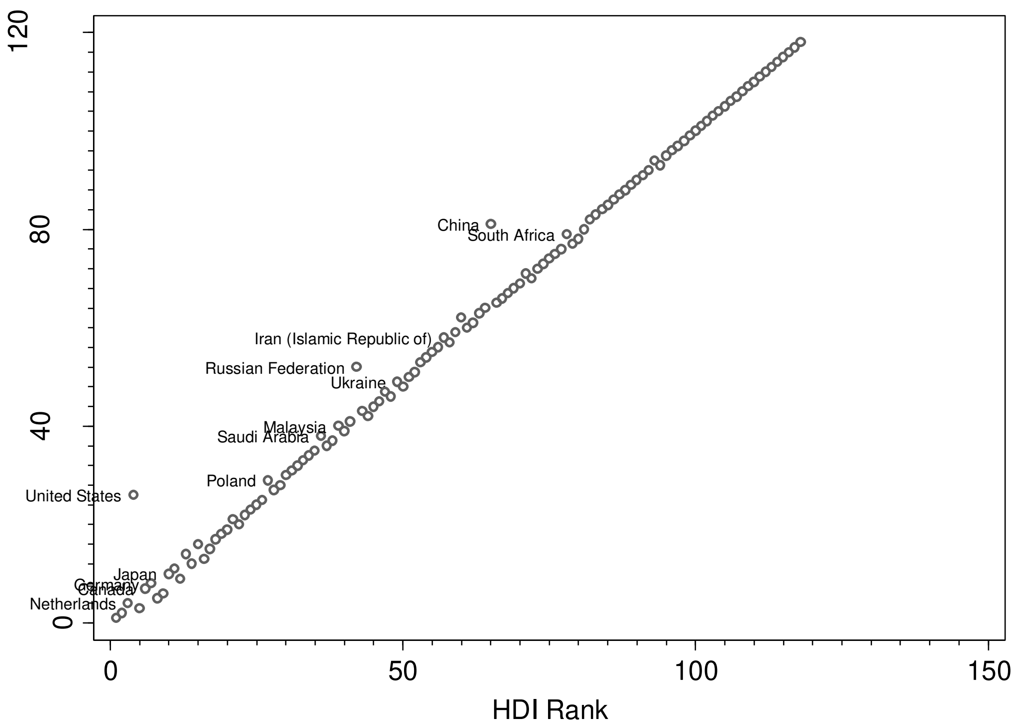
Results with the combined thresholds (the minimum per capita fair share and the maximum global planetary boundary)

Top rank positions lost with SHDI (combined thresholds)

Country	HDI	SHDI	Loss	Rank HDI	Rank SHDI	Number of positions lost
United States	0.9099	0.8125	0.1070	4	26	22
China	0.6871	0.5936	0.1361	65	81	16
Russian Federation	0.7553	0.7212	0.0451	42	52	10
Saudi Arabia	0.7704	0.7648	0.0072	36	38	2
Poland	0.8133	0.8075	0.0072	27	29	2
Turkey	0.6991	0.6968	0.0034	60	62	2
South Africa	0.6194	0.6128	0.0107	78	79	1
Germany	0.9051	0.8879	0.0190	7	8	1
Iran (Islamic Republic of)	0.7074	0.7003	0.0100	57	58	1
Canada	0.9081	0.8990	0.0100	6	7	1
Netherlands	0.9099	0.9079	0.0023	3	4	1
Malaysia	0.7605	0.7585	0.0026	39	40	1
Pakistan	0.5043	0.4979	0.0127	93	94	1
France	0.8844	0.8783	0.0068	15	16	1
Belgium	0.8856	0.8834	0.0026	13	14	1

Source: Own calculations

Rank comparison between original HDI and SHDI (combined thresholds)



Source: Own calculations