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Resilience rankings and trajectories of world's countries

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ABSTRACT

Using an eight-dimensional indicator index, we evaluate the trajectories of resilience of 160 countries over 20 years. Our highly-granular analysis of the current state of the world shows what must happen to control climate change and switch from quantitative to qualitative growth. Assessing the resilience of a country is a complex task prone to opacity and subjectivity. The challenge is to strike a balance between the Earth's biophysical limits and socioeconomic models designed to ignore them. Here we propose a resilience index composed of eight indicators of socioeconomic status (GDP and HDI), natural resources and population (arable land and water resources per capita), energy (supply and renewables), and environmental impacts (greenhouse gas emissions and material footprint). We show that the socioeconomic indicators have improved, while natural resources have been depleting and environmental impacts worsening. We need to reduce the current material footprint 1.5-fold. Average CO_2 emissions per capita must drop by an order of magnitude. Furthermore, population growth and political instability seem to undermine resilience score of a country.

1. Introduction

As this paper will show, the human enterprise is increasingly unsustainable because of the ever-growing number of people, who use ever more energy and liquidate the natural endowment of the planet. On August 24, 2021, typing sustainability in Google yielded 1.22 billion hits. The top hit was this definition of sustainability: *"Meeting the needs of the present without compromising the ability of future generations to meet their needs"*. Thus defined sustainability rests on three pillars: economic, environmental, and social. In practice, they are profit, planet, and people. This subjective, nonscientific and anthropomorphic definition shares few similarities with those in (Brundtland and Visser, 1987; Ripple et al., 2017; Dinerstein et al., 2019; Bradshaw et al., 2021). But what if "profits" trample all else? If "people" are merely the source of cheap labor? And "planet" is a substrate from which the profits are extracted as raw materials (Patzek, 2004; Dinerstein, 2007; Elhacham et al., 2020), soil (Thaler et al., 2021), lumber (Elhacham et al., 2020; Patzek and Pimentel, 2005; Patzek, 2007), water (Stokstad, 2020; *Google Timelapse, Our Ocean, 1984–2020, Google Earth,* 2021) etc., and into which mountains of toxic wastes are dumped (Elhacham et al., 2020; Tiseo, 2020)? What if the "needs of the present" are mostly the needs of the well-to-do, who have privileges that yield opportunities, but decline to take responsibilities that these privileges confer, opting instead for a "net-zero" deception of some kind, e.g., (Dyke et al., 2021)? Moreover, who knows what the needs of future generations will be?

The initial challenge one faces in sharpening the definition above is to eliminate the subjectivity around the needs of the present and to accommodate these needs to the biocapacity of Earth. Observing various trends in the recent past might help us evaluate the progress being made towards "sustainable development". We highlight the following changes in the last 25 years: the world's gross domestic product (GDP) grew 2.4 times; the material footprint doubled; the CO_2 emissions and energy consumption increased by more than half, spawning a population increase of a little less than half (EIA, 2020; UN, 2020). It seems that, on average, we oversupply the present needs, but how will we cater to the needs of future generations?

In 2004, Patzek proposed (Patzek, 2004) a thermodynamic definition of sustainability: *"A cyclic process is sustainable if and only if (i) It is capable of being sustained, i.e., maintained without interruption, weakening or loss of quality 'forever,' and (ii) The environment on which this process feeds and to which it expels its waste is also sustained forever."* The key implications are: (1) A cyclic process must not reject waste chemicals into the environment, i.e., its net waste production must be close to zero "forever". (2) A sustainable cyclic process must not reject heat into the environment at a rate that is too high for the Earth to export this heat to the universe; otherwise, the environmental properties will change. (3)

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The operational definition of “forever” Patzek chose for human civilization was 5000 years, the age of Egypt’s oldest surviving wood structure. (4) Almost everything we do is unsustainable, because all major human activities are *linear* and *irreversible* (mining of minerals, oil, gas, coal, soil, groundwater, ecosystems, biodiversity, etc.). We also dump toxic chemicals everywhere in the environment (atmosphere, water, and land).

In view of the remark (4) above, no scientist can claim that the human economy is sustainable. At best, one may try to construct a consistent measure of how *resilient* the countries around the world are relative to one another. Here “resilient” means a country capable to recover from some difficulties for some time; it is the country’s toughness and elasticity. Resilient countries can be very different. For example, Paraguay and Iceland are both resilient, but for different reasons. Their modes of future failure will also be different. In this paper, we construct an eight-dimensional resilience measure for some 160 countries around the world, and track this measure for all countries over 20–25 years. Allowing for the customary misspelling of resilience as sustainability, we will use these two terms interchangeably, with a clear understanding that *nothing* in the human economy is thermodynamically and ecologically sustainable.

To make our eight-dimensional (octagon) approach to quantifying global resilience accessible to diverse audiences, we have aligned its eight indices with the most popular definition of ‘sustainability’ described above. This definition is so popular because it focuses on the “needs” of the living people, while in fact, to satisfy those needs the global economy is pursuing monetary goals by liquidating ecosystems and undermining life-support functions future generations will need to survive (Toth and Szigeti, 2016). Climate change is one of these impacts that will ravish food systems (Wheeler and von Braun, 2013), biodiversity (Dinerstein et al., 2019; Bar-On et al., 2018; Arneth et al., 2020; Raven and Wagner, 2021), and social dynamics (Roche et al., 2020). The concept of “planetary boundaries,” or absolute limits of growth, (Rockström et al., 2009) brings into focus the carrying capacity of our planet and ecological overshoot. The decline of natural resource availability – including loss of biodiversity – will make it impossible to maintain current lifestyles (Fuso Nerini et al., 2019; Ceballos et al., 2020). Another critical factor is power supply. It will be difficult to change the status quo and forgo in the next 20 years the 15 TW of primary power from fossil fuels, which powered the human world 313 days in 2019 while adding to global warming for centuries (Ricke and Caldeira, 2014; Zhang and Caldeira, 2015). Since 1830, power production and population growth went hand-in-hand (see SI Fig. 1). Without exosomatic power, there is no quantitative socioeconomic growth, and several of the ‘Sustainable Devel- opment’ Goals of the United Nations may be unachievable (Hagens, 2020; Fuso Nerini et al., 2018). Relevant trends in the global economy are shown in SI Figs. 1 – 5.

We accept that resilience has three pillars - environmental, social, and economical. We analyze resilience from a perspective that covers (1) some of what nature provides (arable land and water); (2) how severely we are impacting and depleting the ecosphere (greenhouse gas emissions and material footprint); (3) whether there is energy available to perpetuate the complex systems in place (energy supply) and how much of this energy is non-fossil (renewables); (4) what access to goods and services (GDP) there is; and (5) how well a basic quality of life (HDI) is delivered.

The elusive sustainability (resilience, really) is a multifaceted and complex *idea* with its science which attempts to create knowledge that solves key problems (Patzek, 2007; Kates et al., 2001). Sustainability’s complexity demands a complete restructuring of how institutions produce relevant knowledge (Patzek, 2004; Cash et al., 2003). Forecasting sustainable development hinges on science, current knowledge, and tools. The desire to produce a sustainability index is not new. At present, there are analyses and indices for a variety of large systems, such as food (Chaudhary et al., 2018), energy systems (Evans et al., 2009; Cartelle Barros et al., 2015), food-energy-water nexus (Ozturk, 2015), local communities (Valentin and Spangenberg, 2000; Lindsay et al., 2020; Reed et al., 2006), and countries (Nilashi et al., 2019; Nourry, 2008). Furthermore, a sustainability index can be developed with a variety of tools and methodologies from multi-criteria analyses (Rowley et al., 2012; Giampietro et al., 2006; Etxano and Villalba-Eguiluz, 2021) to machine learning (Nilashi et al., 2019). Furthermore, the use of partially ordered sets could help to account for the complexity involved in sustainability/resilience (Fattore and Arcagni, 2021). Specifically, there exist the widely accepted ecological footprint (Rees, 1992; Wackernagel, 1994) and the environmental performance index (Hsu and Zomer, 2016).

Nevertheless, despite the progress in understanding the issues and developing the corresponding tools, there are no universally accepted and deployed sustainability or resilience indices. Here is why: a viable index must facilitate both qualitative and quantitative evaluations (Moldan et al., 2012). The difficulty lies in selecting and interpreting indicators that compose this index (Moldan et al., 2012), and each particular selection is prone to subjectivity (Morse et al., 2001) that could bias the index. More importantly, a popular resilience index will affect policymaking (Hezri and Dovers, 2006) and will therefore be subject to intense political negotiations. In the end, a useful resilience index must be concise, easy to communicate, and global (Hák et al., 2016).

The eight indicators of our index are readily available from the well-known databases from, e.g., EIA, IEA, FAO, UN, World Bank, etc. Public domain data make this index accessible to large audiences. To help in engaging different spheres of civil society, we present key information in a simple graphical form. We evaluate how different countries have been performing for up to 25 years, and identify global trends and critical aspects of development. Limitations and potential biases of our index are discussed. The proposed thresholds for our resilience indictors can be adjusted easily.

2. Methodology

This section provides all the information needed to understand and replicate the resilience index. Section 2.1 describes the selected indicators and thresholds adopted for each of them. Section 2.2 provides the details of indicator normalization and score calculation. Fig. 1 shows a flowchart that describes the steps necessary to calculate the resilience octagon index.

2.1. Indicators and thresholds

To evaluate a country’s resilience properly, we selected indicators based on three pillars – social, economic, and environmental. The selected indicators and threshold criteria are:

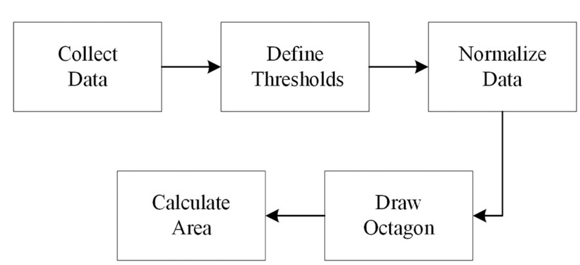

Fig. 1. Procedure to arrive at a resilience score. The initial step is to collect data from the databases available for the selected indicators. Secondly, we set thresholds for each indicator. Afterwards, the indicator values are normalized with the adopted thresholds. The normalized values are assigned to the vertices of the unit octagon. The final step consists of calculating the area of the polygon thus formed.

1. **Gross Domestic Product (GDP)** is an economic criterion providing one measure of a country's level of economic activity. GDP is a monetary index (the value of final sales of goods and services), and it does not reflect the true well-being of the country (Stiglitz, 2020). The threshold adopted here is $30,000 for GDP per capita adjusted for purchasing power parity (PPP). This value is an entry-level for a country to be classified as high-income (Bank, 2019; Statistics Times, 2018). The reference data are from the U.S. DOE EIA (EIA, 2020), and the PPP is referenced to the year 2015.
2. **Human Development Index (HDI)** is a composite index based on access to education by the expected years of schooling children, the living standard from gross national income per capita, and life expectancy at birth (UN, 2018). HDI is already scaled between 0 and 1, and there is no threshold to define. We note that HDI is inherently imprecise, and usually overestimates a country's advancement by underestimating the rule of law, self-governance, advanced schooling, and research infrastructure. Also, HDI seems to be incompatible with ecological stability (Hickel, 2020). An interesting attempt at extending and improving HDI was just published (Lucia and Grisolia, 2021). In our more complex approach, HDI is but one of eight indicators. The reference data are from UNDP (UNDP, 2021).
3. **Energy Supply** assesses energy independence with the ratio of energy produced domestically per year (power) to total power consumed. The threshold we chose separates countries that can supply their total power demand from those that cannot. The reference data for primary energy consumption and production are from EIA (EIA, 2020).
4. **Renewable Energy** evaluates the fraction of total power produced that is generated by the alleged "renewables" and nuclear reactors. Our threshold separates countries that can supply their power demand from renewable and nuclear sources from those that cannot. The reference data are from EIA (EIA, 2020).
5. **CO_2 Emissions** are a must from environmental perspective. Adequate threshold determination is difficult because this threshold should be dynamic, accounting for the remaining carbon budget (WBGU, 2009; Friedlingstein et al., 2014). The adopted value is 2 tCO_2/yr/capita. We lump all emissions as CO_2 equivalent emissions to account for CO_2, CH_4, NOx, and change of land use (Ritchie and Roser, 2020; Houghton and Nassikas, 2017).
6. **Arable Land** refers to the land suitable for crop production (FAO, 2020a). Cultural aspects can significantly interfere with defining a threshold for the minimum arable land per capita. The type of diet matters because what is eaten affects this indicator more than how much is eaten (Ritchie, 2007). Depending on a diet, the required area can vary from 0.18 ha/capita to 0.86 ha/capita (Peters et al., 2007). The selected threshold is 0.5 ha/capita, allowing a diverse diet with some meat consumption. The data are from FAO (FAO, 2019).
7. **Water** is the total internal renewable water resource per capita. According to FAO (FAO, 2020b), an average of 1000 m^3/yr/capita is a minimum required to sustain life and guarantee agricultural production. The reference data are from AQUASTAT (FAO, 2014).
8. **Material Footprint** is the net material consumption. It is the sum of domestic extraction plus the raw material equivalent of imports and minus the raw material equivalent of exports (UN, 2020). Defining the sustainable use of materials ranges from a target for total material consumption to consumption according to the type of material (biotic or abiotic) (Bringezu, 2015; Lettenmeier et al., 2014). The selected threshold is 8 t/yr/ capita (Lettenmeier et al., 2014). The data used for the material footprint are from the UN International Resource Panel (UN, 2020).

2.2. Resilience score

The initial step consists of normalizing the indicators between 0 and 1. Each indicator that has a threshold as a *lower* bound (GDP, energy, renewables, arable land, and water) receives the maximum score of 1 when its value is equal to or greater than the threshold. When this indicator's value is *smaller* than the threshold, the score is this value divided by the threshold (a fraction). Thus, e.g., a water indicator less than one is *bad*.

Each indicator that has an upper bound threshold (CO_2 emissions and material footprint) is set to 1 if its value is equal to or below the threshold. When an indicator's value is *greater* than its threshold, the score is the threshold value divided by the actual value of the indicator (a fraction). Thus, e.g., a CO_2 indicator *less* than one is *bad*.

The resilience score is calculated as the polygon area whose vertices are set by the scaled indicators. The radial distance to each vertex is the normalized value of the corresponding indicator. The allocation of an indicator to a given vertex is based on the highest linear correlation between this indicator and another one; thus, achieving an optimized distribution. This distribution minimizes the contribution from correlated indicators – see SI Fig. 6 for the correlation matrices and *p*-values.

Some of the potential methods of calculating resilience scores are:

1. **Polygon Area** is the area of a polygon, in which each vertex represents an indicator. Radial distance to a vertex is a normalized value of an indicator assigned to this vertex (see SI Fig. 6). This area can be obtained in two ways:
   1.1 **Optimized:** the order of the indicator vertices is based on linear correlations between pairs of variables (see SI Fig. 6).
   1.2 **Permutated:** areas of the polygons are constructed from all permutations of vertices, and the mean area is calculated (see SI Fig. 7).
2. **Summation (Σ):** all indicators (I_n) are summed $\left(Score \sum_{n=1}^{8} I_n\right)$
3. **Multiplication (Π):** all indicators are multiplied $\left(Score \prod_{n=1}^{8} I_n\right)$

2.3. Categorical classification

A categorical classification was made to analyze trends in the indicator scores by classifying them as low, middle, and high. According to the established threshold, the low classifications mean a poor or critical score of the selected indicator. The middle classification indicates that an indicator is not in a critical condition. The high category means a satisfactory score; the indicator is on the *safe* side of its threshold criterion.

The intermediate values of the categorical classification are: Carbon dioxide emissions 0.4 to 1; Energy supply 0.5 to 0.9; GDP 0.4 to 1; HDI 0.55 to 0.8; Land 0.4 to 1; Material footprint 0.5 to 1; Renewables 0.25 to 0.5; Water 0.5 to 1. If an indicator's value is below the lower threshold, it is classified as "Low". When the indicator value is above the upper threshold, it is classified as "High".

3. Results and discussion

3.1. Comparing approaches: limitations and biases

Different methods of calculating a resilience index lead to different results and potentially inject biases towards certain conclusions. The Π approach amplifies the differences, requiring a country to have all indicators with reasonable values for a good total score. A single indicator with a low value severely penalizes the resilience index's final score. The Π approach score is only as good as the worst indicator. This approach emphasizes a country's key weakness, which will be the first reason for this country to fail during extreme events in climate and politics.

Conversely, the Σ approach is weakly affected by a single indicator. Strong indicators compensate for weak ones. This compensation could be questioned. For example, could ample energy mitigate arable land and water scarcity? For how long? Similarly, increasing renewables will increase energy supply and probably reduce CO_2 emissions. To what extent are these compensations reliable? Also, it is important to mention that certain compensations could easily occur. As we can see, each case needs to be evaluated separately.

The optimized octagon approach balances the indicators scores; a single indicator cannot severely penalize or compensate others in the resilience score.

Fig. 2 displays the accumulated resilience scores of the maximum resilience available to all 166 countries in the database in 2015. These countries are ordered from the most vulnerable to the most resilient ones. If each country had a perfect score, their common maximum score value would be $2.83/\pi = 0.9$. Thus 166 countries would accumulate ~ 150. The earth's countries accumulated 59 according to the summation (Σ) score, 29 according to the optimum octagon score, and 0.4 according to the product (Π) score. The three methods (summation, optimized octagon and multiplication) demonstrate that the summation acts as an upper bound and the multiplication as a lower bound on the resilience indices (see SI sections 2 and 3 for details).

Notice that the world is already either very vulnerable or just vulnerable according to the optimum octagon score – scoring 0.29 out of 1. If this is not a warning to all humans, we do not know what is. Parenthetically, the unrealistically high Σ score might be preferred by the world's politicians and international organizations, and the brutal Π score by the climate change, biodiversity and ecology experts. The Π score, according to which the world is only 0.4 resilient, is the direst warning produced by our analysis. Recall that the Π score makes a country as good as its weakest indicator. This score may actually be most descriptive of the real world with climate warming, the ensuing social unrest, and large-scale human migrations that will disrupt or annihilate global supply chains. The ongoing sixth mass extinction may be the most serious environmental threat to the persistence of our global civilization, because it is irreversible (Ceballos et al., 2020). Therefore, loss of biodiversity and habitats (Ripple et al., 2017; Dinerstein et al., 2019; Bradshaw et al., 2021; Dinerstein, 2007; Elhacham et al., 2020) may be the most important index that will have to be added once sufficient data are collected for each country.

The following analysis is based on the more conservative optimized octagon approach. The scores from the optimized approach are between the Π and Σ approaches and provides a wide enough distribution of the resilience scores to facilitate comparisons among countries.

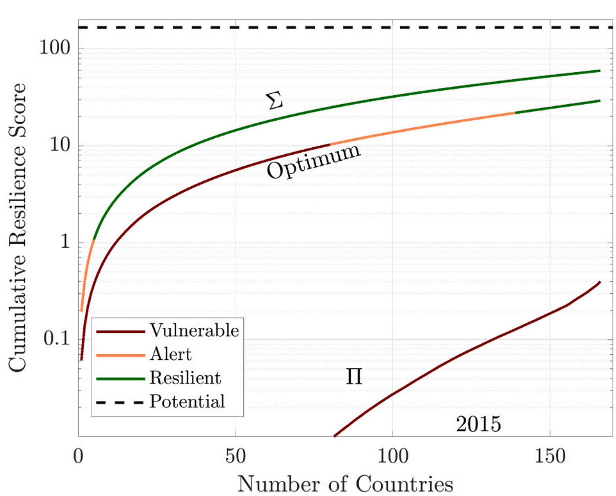

Fig. 2. Cumulative resilience score of the world in 2015. It shows the accumulated resilience scores of 166 countries. In 2015, the earth's countries accumulated 59 points according to the summation (Σ) score, 29 according to the optimum octagon score, and 0.4 according to the product (Π) score. The scores were sorted in ascending order from the most vulnerable to most resilient countries. *Two-thirds* of the Earth's countries are vulnerable.

3.2. Global perspective

The resilience scores of all assessed countries are shown in Fig. 3. Regional patterns may emerge from the geog- raphy and socioeconomic characteristics of the neighboring countries. The planet's resilience score has been sliding uniformly (see SI section 4). Our approach produces global resilience scores that are negatively affected (i.e., decrease) with population growth and high population density.

Typical characteristics of the most resilient countries are the abundance of natural resources and low population density. As we can see, some developed countries, considered resilient by many, do not appear in this ranking that seems to rectify misconceptions in characterizing a genuinely resilient country.

The common traits of the least resilient countries are limited natural resources and high population densities. Overall, the developed and vulnerable countries are thriving due to international trade. They compensate for the lack of natural resources by imports and export the unavoidable environmental deterioration elsewhere. This observation highlights the fragility of global trade; a major interruption could cut off these developed countries from vital supplies. The developed countries also face other impacts from their activities - depletion of domestic resources, e.g., oil exploitation, and environmental impacts of tourism. International trade is highly desirable economically, but it accelerates resource exploitation, leading to stock depletion just to maintain present consumption (Riekhof et al., 2019). This situation contradicts sustainable development and is one of the numerous social traps (Costanza, 1987).

An additional observation is related to the relatively highly ranked countries that are underdeveloped. These countries seem resilient because they lack access to consumption and have small material footprints and low levels of CO_2 emissions. Knowing that GDP is one of the indicators growing quickly, we should expect a worsening of these emerging economies' scores. A great challenge is how to develop these countries sustainably - raising concerns about whether world community measures development correctly.

3.3. Resilient and vulnerable countries

The resilience octagon posits that harmony and balance among all eight indicators are key to resilience. Fig. 4 illustrates this observation. Countries with good scores for the majority of indicators are deemed to be resilient, while the countries with only a few indicators that are not critically low are vulnerable. An acute imbalance of indicators is a strong predictor of vulnerability (see SI Fig. 7).

Fig. 4a shows the resilience octagon for some of the most resilient countries. Their indicators span a large area of the plot in the range of 45% to 55% of the maximum area, which means that these countries achieve good scores in the majority of the indicators. It seems obvious that a truly resilient country must supply its own needs with minimal environmental impacts. Thus, under the applied criteria, high scores for all indicators imply strong resilience.

Fig. 4b shows some of the most vulnerable countries. They span small areas of the octagon in the range of 9% to 14%. These countries have low values of some indicators, but they might have one or two high ones. The vulnerable developed nations have strong socioeconomic indicators (GDP and HDI) and/or a strong energy indicator for the hydrocarbon-rich countries. The underdeveloped nations mainly have good CO_2 emissions and material footprint indicators that are associated with poverty rather than resilience. Expectedly, small countries with limited natural resources and excessive populations are most vulnerable.

There are two distinct groups of vulnerable countries that are easy to identify - oil producers and small islands. The oil-producing countries have a strong dependence on fossil fuels for energy supply that results in high CO_2 emissions, and meager renewable energy sources. In addition, most of these countries are located in a hot and arid climate and have limited/nonexistent arable land and water resources. The small islands

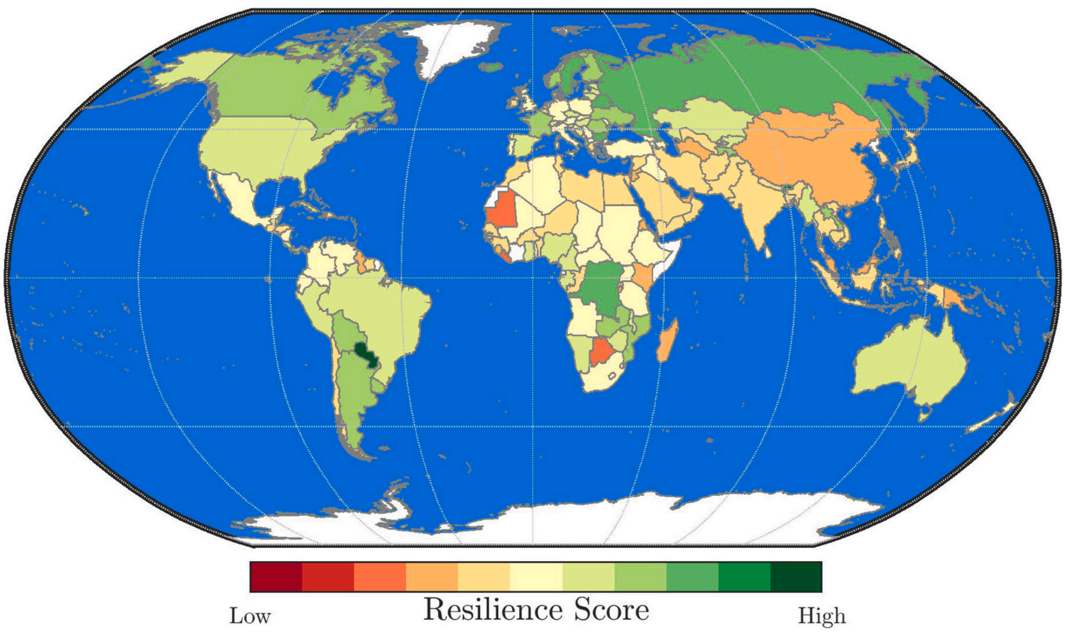

Fig. 3. Global resilience. The most resilient countries are greenish, while the least resilient countries are reddish. The contrast in the colors is based on a normalized distribution of the score values. More resilient countries have low population density and high availability of natural resources. The high population density in the Asian countries results in their low resilience scores. Due to the limited biophysical carrying capacity of the MENA region, this region is grossly overpopulated. The data are for the year 2015, with the white areas missing. The country borders are plotted using (Greene et al., 2019).

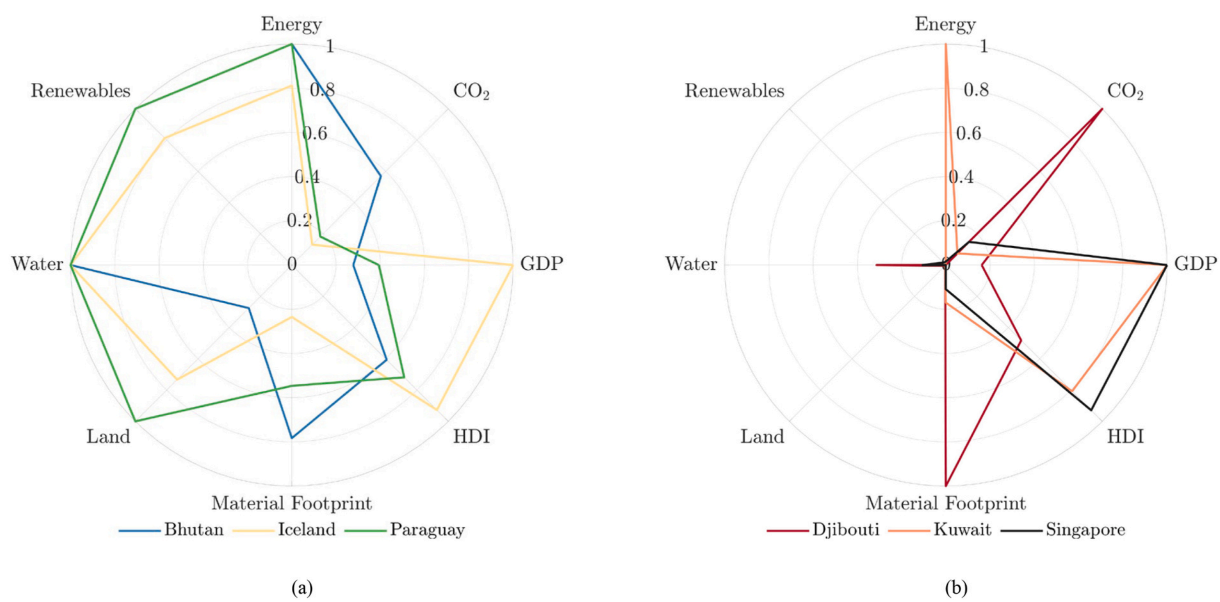

Fig. 4. Resilience octagon. (a) Resilient countries fill large areas of the octagon. (b) For vulnerable countries, only small areas of the octagon are filled. Reference year: 2015.

are mostly finance tax havens or tourism hubs. They have limited natural resources and are energy deficient. Some of these countries are entirely dependent on resource imports from foreign nations to keep their economies working. These countries are negatively impacted when a major hurricane hits or the sea level rises (see SI sections 4 and 6 for the resilience trends and scores of the G20 and other selected countries).

Fig. 5 shows the countries that are consistently ranked among the most and least resilient ones. Their maximum count is 26 over the studied period from 1990 to 2015. Overall, there are consistencies in the membership of the dominant groups of countries in both cases. Other countries appear sporadically, only when they are ranked near the top or bottom twenty.

The most resilient countries in Fig. 5a are diverse and not commonly considered as resilient. They range from developed to emerging countries, revealing that there is no unique recipe for a country to be resilient.

The most vulnerable countries in Fig. 5b are small. Here again, the group is diverse, usually fitting the typical profile described above. However, upon checking this historical ranking, we learn that besides the dominant group, the countries that appear in the most vulnerable group have faced or are currently facing political instability. This situation mainly affects a country's socioeconomic indicators. Political instability cascades into all other indicators, lowering them, and this effect can last for a long time. Political instability is not only bad for business, but also for resilience.

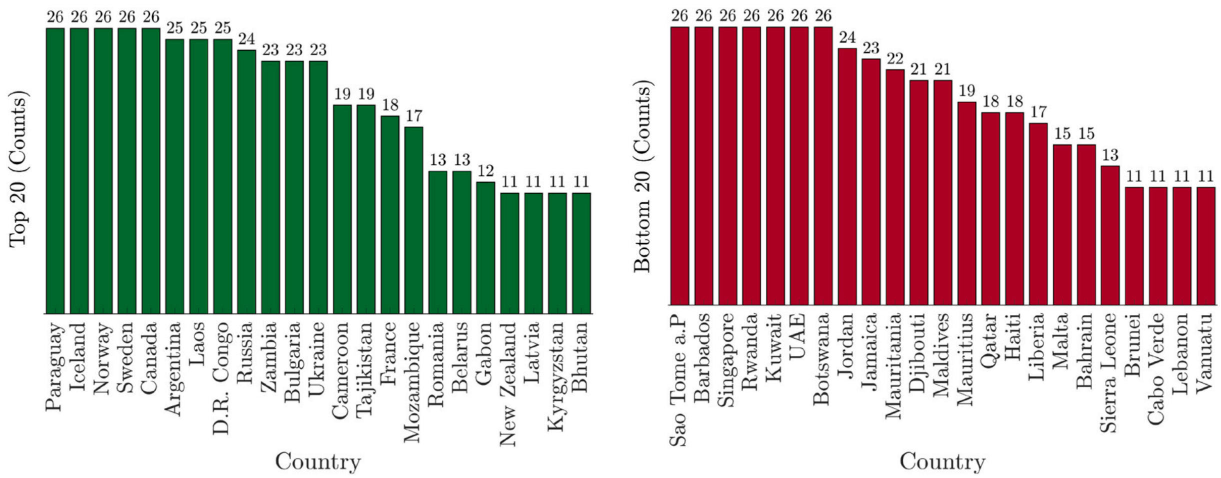

Fig. 5. Histograms: (a) Resilient countries. The counts refer to the number of times a country appeared as one of the twenty most resilient countries. (b) Vulnerable countries. The counts refer to the number of times the country ranked as one of the twenty most vulnerable countries. The maximum score is 26 in both cases, referring to the period from 1990 to 2015.

3.4. Indicator trends

Fig. 6a shows a categorical distribution of the indicators for 2015. When a country is classified in the low category, it must be interpreted as critical; it needs improvements when it is classified in the middle category, while a high classification indicates that a country is within the proposed resilience targets. We should point out that half of the indicators are in a critical state. The critical condition of the energy indicator shows that most countries are dependent on imports to supply their domestic needs, mostly with fossil fuels. Consequently, renewables are the most critical indicator that confirms dependence on external fossil fuels to cover energy needs. The GDP indicator shows that many countries have underdeveloped economies – development in these countries could mean improved living standards but this would be reflected as an increment of their material footprint and CO_2 emissions. The arable land and water indicators highlight overpopulation. The numerous countries in the "low" category cannot feed their populations without imports and/or have insufficient water supply systems.

Fig. 6b shows trends in the eight indicators, comparing data in 1992 and 2015. Improvements occurred mainly in the socioeconomic indicators, GDP and HDI, and in the expansion of renewables. It is important to mention that the improvement in renewables is illusory. First, Fig. 6a shows that most countries are in critical states regarding renewable energy resources, and their improvement is an advance from zero to a value near zero (see SI Fig. 1); second, modern renewables (mostly wind turbines and solar PV) are merely replaceable, not renewable, and are heavily subsidized by fossil fuels (Seibert and Rees, 2021). The natural resource indicators worsened, mainly due to population growth, which means that more people share a dwindling stock of finite resources; here arable land and water. Land and water mismanagement and misuse are the common aggravating factors. The worsening of the material footprint indicator is a side effect of development, reflecting increased living standards and easier access to goods and services. CO_2 emissions show a balance of improvement and decline. This metric is ambiguous. While we observe improvements (lower emissions) in selected countries, global emissions are increasing. Additionally, Fig. 6a shows that most countries are in critical status. One might question if this balanced improvement/worsening occurs by a

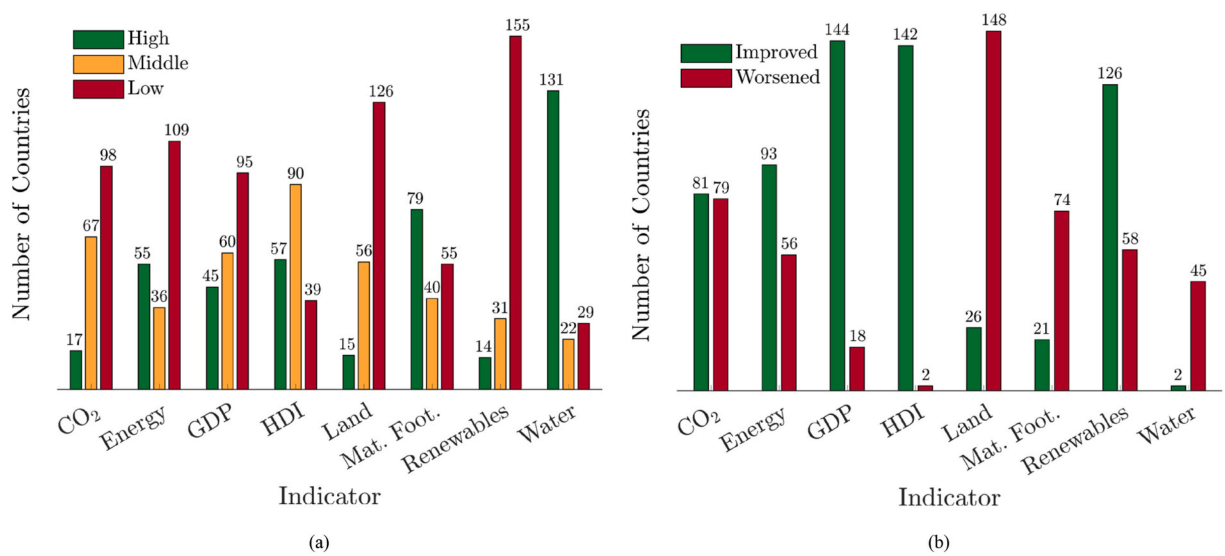

Fig. 6. Indicators. (a) The indicator score is subdivided into three categories: low or critical, middle or needing improvement, and high that is within the proposed resilience targets. The number above each bar is the number of countries in a given category. The latest classification is for the year 2015. (b) Indicator changes. Each green bar represents the countries that improved an indicator. Each red bar groups the countries that worsened an indicator. The comparison is between 1992 and 2015.

transference of emissions, (e.g., heavy industry moving towards cheap labor), or that the improvements in some countries are nullified by the worsening in other countries, where increased emissions are a direct consequence of development. Note that the indicators with scores equal to one in 1992 and 2015 might have worsened or improved in absolute terms. Indicator changes below their respective thresholds do not modify the score and are *not* detected by our approach (see SI section 5 for indicator trends).

Fig. 6 suggests a path for improvement. Access to energy is the most important element of sustainability. Expansion of renewables can improve three indicators (with the reservations noted above): 1) the share of renewables in the energy mix; 2) the structure of energy supply (renewable resources are local); and 3) CO_2 emissions. Furthermore, this measure may bring socioeconomic benefits, such as job creation (Ram et al., 2020). Proper management and preservation of natural resources, i.e., of arable land and water are essential to a sustainable future. It seems clear that overpopulation is the key factor driving decline in most worsening indicators. Implementation of population policies that lead to an eventual population reduction is a prerequisite for long-term sustainability.

3.5. Impacts on policy making

The resilience octagon makes it possible to track the impact of the adoption of different policies. The present study shows the effect of the previous actions that produced the observed status in 2015 (see SI sections 4 to 6). While the resilience score is a reference number tracking the current situation, the qualitative information expressed by the polygon shape provides insights into where the country is heading.

Fig. 7 shows the evolution of the World, Afghanistan, and Denmark. We notice that at a global level, the resilience score is worsening. Afghanistan and Denmark were selected because in 1995, they had similar resilience scores. Afterward, they took very different paths. Denmark improved its apparent resilience by maintaining its population stable and increasing its share of renewables, thus increasing its energy and CO_2 scores. In contrast, Afghanistan worsened significantly over the analyzed period. Its population almost doubled despite the continuous wars, decreasing the scores of natural resources (water and arable land). The human development index also suffered. Note that the polygon shapes remained unchanged for Denmark and changed somewhat for Afghanistan, but the respective areas diverged, increasing for Denmark and decreasing for Afghanistan.

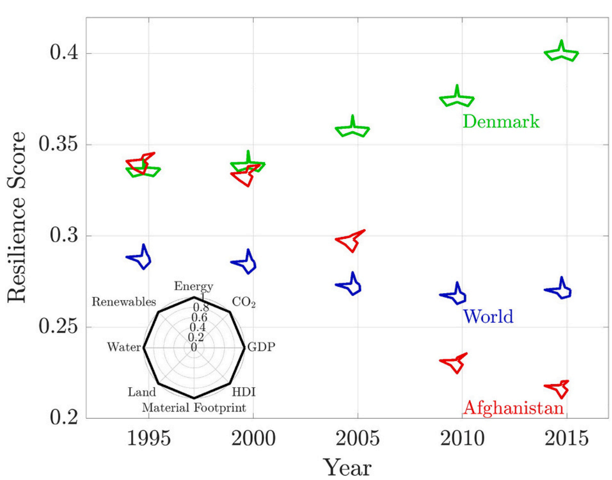

Fig. 7. Resilience histories. The *y*-axis represents the area of the optimized resilience octagon, normalized by the maximum score. The black octagon shows the optimized permutation of the indicators. The blue polygons represent the world, whose score is decreasing, mainly due to the depletion of natural resources (land and water), an increase of the material footprint, which could be linked to population growth and improvement of living standards or urbanization. The green polygon depicts Denmark that has improved mainly due to an increase in renewables and reduction of CO_2 emissions. The red polygon depicts Afghanistan, whose scores have been worsening, mainly due to a reduction of arable land and renewables, which can be associated with growth of the population that almost doubled and has been made worse by climate change. War is factored in the HDI score that will take another large hit after September 2021.

Countries with similar resilience scores in Fig. 7 can be following different paths. Beyond the resilience score, we must appreciate the qualitative aspects of the octagon. Qualitative interpretation improves understanding of trends and avoids a simple numerical reduction that can be misleading (Arcagni et al., 2021). The octagon approach helps to identify national policy strengths and weaknesses; the current polygon shape can provide clues about where a country is heading (see SI section 6). Furthermore, follow-up studies will allow one to compare and track the impacts of particular national policies. Countries often develop along similar lines. Identifying a country that had a similar polygon shape at a previous point in time can provide valuable insights into the possible future path of a second country and suggest policy initiatives to take or avoid. The possibility of projecting the future development of a country, by knowing its previous and current states, provides important insights to decision-makers in choosing and implementing optimal policies and actions.

4. Conclusions

The eight-dimensional resilience index developed here pinpoints the resilient and vulnerable countries worldwide. All versions of this index lead to similar conclusions. Countries with ample natural resources will be more resilient in face of crisis. Conversely, the apparently successful countries, whose advanced economic development (high GDP per capita) allows them to import natural resources from foreign nations will prove more vulnerable in the long run.

Over the 20- to 25-year periods analyzed, the following global trends have been identified: socioeconomic improvement that seems to be associated with natural resource depletion; energy-wise, there has been a slight improve- ment in energy supply from expanding renewables, but this expansion does not even cover the year-on-year increases in fossil fuel consumption and renewables remain far from displacing fossil fuels (except for electricity generation in a few countries); population growth and income increases combined with the resultant depletion of resources are the proximal causes of the deteriorating global resilience. We have not explicitly assessed the role of climate change, but it will likely emerge as a major influence on developmental trends in coming years.

Beyond the scope of this work, additional key indicators (climate and biodiversity) and/or thresholds could be investigated. The developed algorithms are available as supplementary materials, giving all an opportunity to explore specific queries and add new indicators.

It is clear that the world's countries have been dealt unequal hands in the global game of prosperity, survival, and domination: their geographical locations, topographies and local climates, neighboring countries, surface areas, natural resources, biodiversity, mineral resources, etc., all play determining roles. The political systems, human development, and populations of these countries have also evolved quite differently, with expected variable consequences. It is evident from this analysis that most countries are in acute ecological overshoot (Rees, 2020), and their long-term viability is uncertain in a rapidly changing world. Overshoot is eventually a terminal condition. Yet it is also clear that most people worldwide are in utter denial of the severity of our current predicament. The distal cause of this denial operates beneath consciousness: *Homo sapiens* has evolved as a dogged K-strategist in the competition for resources and habitat. The very behavior that made our species successful in dominating the Earth in simpler times has become a potentially fatal maladaptation in the rapidly changing environment of our own making (Rees, 2010).

To reduce ecological overshoot and slow the sixth extinction of life on the Earth, it is essential that global society adapt to using much less of everything and cooperate in reducing human population. Regrettably, the resistance of entrenched interests in positions of political and economic power, combined with the normal defensive instincts (e.g., spatial, temporal and social discounting) and emotions of ordinary people prevent the world community from acting on the objective reality that our *reasoning* brain (neocortex) registers.

To engineer – even to contemplate – a coordinated economic contraction opposes everything that people in the techno-industrial societies have been biologically and culturally programmed to do. However, nothing will change until we learn to transcend both expansionist human nature and the reinforcing cultural myth of perpetual growth and continuous technological development. History is not encouraging. More granular recommendations – such as a global one-child policy – have been voiced with little success by countless authors over the last century. Dare we hope that the social scientists, psychologists, and economists reading this paper will begin to articulate novel yet actionable recipes that will enable the world's most advanced and/or populated societies to change course dramatically? Only then will we avoid what would otherwise be an inevitable collision with biophysical reality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Drs. Bolson and Yutkin were supported through Baseline Research Funding from KAUST to Prof. Patzek.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cis.2022.102600.

References

Arcagni, A., Fattore, M., Maggino, F., Vittadini, G., 2021. Some critical reflections on the measurement of social sustainability and well-being in complex societies. Sustainability 13, 12679. https://doi.org/10.3390/su132212679. https://www.mdpi.com/2071-1050/13/22/12679.
Arneth, A., Shin, Y.-J., Leadley, P., Rondinini, C., Bukvareva, E., Kolb, M., Midgley, G.F., Oberdorff, T., Palomo, I., Saito, O., 2020. Post-2020 bio- diversity targets need to embrace climate change. Proc. Natl. Acad. Sci. 117 https://doi.org/10.1073/pnas.2009584117.
Bank, W., 2019. New Country Classifications by Income Level: 2019-2020.
Bar-On, Y.M., Phillips, R., Milo, R., 2018. The biomass distribution on earth. Proc. Natl. Acad. Sci. 115 (25), 6506–6511. https://doi.org/10.1073/pnas.1711842115.
Bradshaw, C.J.A., Ehrlich, P.R., Beattie, A., Ceballos, G., Crist, E., Diamond, J., Dirzo, R., Ehrlich, A.H., Harte, J., Harte, M.E., Pyke, G., Raven, P.H., Ripple, W.J., Saltré, F., Turnbull, C., Wackernagel, M., Blumstein, D.T., 2021. Underestimating the challenges of avoiding a ghastly future. Front. Conserv. Sci. 1, 9. https://doi.org/10.3389/fcosc.2020.615419.
Bringezu, S., 2015. Possible target corridor for sustainable use of global material resources. Resources 4 (1), 25–54. https://doi.org/10.3390/resources4010025.
Brundtland, G.H., Visser, W., 1987. Our Common Future: World Commission on Environment and Development, Tech. rep., United Nations.
Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Cano Gochi, A., 2015. Assessing the global sustainability of different electricity generation systems. Energy 89, 473–489. https://doi.org/10.1016/j.energy.2015.05.110.
Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustain- able development. Proc. Natl. Acad. Sci. U. S. A. 100 https://doi.org/10.1073/pnas. 1231332100.
Ceballos, G., Ehrlich, P.R., Raven, P.H., 2020. Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction. Proc. Natl. Acad. Sci. 117 (24), 13596–13602. https://doi.org/10.1073/pnas.1922686117.
Chaudhary, A., Gustafson, D., Mathys, A., 2018. Multi-indicator sustainability assessment of global food systems. Nat. Commun. 9 (1), 1–13. https://doi.org/10.1038/s41467-018-03308-7.
Costanza, R., 1987. Social traps and environmental policy. BioScience 37 (6), 407–412. https://doi.org/10.2307/1310564.
Dinerstein, E., 2007. Global and local conservation priorities. Science 318 (5855), 1377–1382. https://doi.org/10.1126/science.318.5855.1377b.
Dinerstein, E., Vynne, C., Sala, E., Joshi, A.R., Fernando, S., Lovejoy, T.E., Mayorga, J., Olson, D., Asner, G.P., Baillie, J.E.M., Burgess, N.D., Burkart, K., Noss, R.F., Zhang, Y.P., Baccini, A., Birch, T., Hahn, N., Joppa, L.N., Wikramanayake, E., 2019. A global deal for nature: guiding principles, milestones, and targets. Sci. Adv. 5 (4) https://doi.org/10.1126/sciadv.aaw2869.
Dyke, J., Watson, R., Knorr, W., 2021. Climate scientists: concept of net zero is a dangerous trap. Conversation. April. https://theconversation.com/climate-scientists-concept-of-net-zero-is-a-dangerous-trap-157368.
EIA, 2020. Primary Energy.
Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y.M., Milo, R., 2020. Global human-made mass exceeds all living biomass. Nature 588, 7838. https://doi.org/10.1038/s41586-020-3010-5.
Etxano, I., Villalba-Eguiluz, U., 2021. Twenty-five years of social multi-criteria evaluation (smce) in the search for sustainability: analysis of case studies. Ecol. Econ. 188, 107131 https://doi.org/10.1016/j.ecolecon.2021.107131.
Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of Sustainability Indicators for Renewable Energy Technologies. jun. https://doi.org/10.1016/j.rser.2008.03.008.
FAO, 2014. Aquastat Database.
FAO, 2019. Faostat- Land Use.
FAO, 2020a. Indicators- Agriculture, Tech. Rep. FAO.
FAO, 2020b. World Water Resources by Country.
Fattore, M., Arcagni, A., 2021. Posetic tools in the social sciences: A tutorial exposition. In: Measuring and Understanding Complex Phenomena. Springer International Publishing, pp. 219–241. https://doi.org/10.1007/978-3-030-59683-5_15.
Friedlingstein, P., Andrew, R.M., Rogelj, J., Peters, G.P., Canadell, J.G., Knutti, R., Luderer, G., Raupach, M.R., Schaeffer, M., Van Vuuren, D.P., Le Quéré, C., 2014. Persistent growth of co2 emissions and implications for reaching climate targets. Nat. Geosci. 7 (10), 709–715. https://doi.org/10.1038/NGEO2248.
Fuso Nerini, F., Tomei, J., To, L.S., Bisaga, I., Parikh, P., Black, M., Borrion, A., Spataru, C., Castán Broto, V., Anandarajah, G., Milligan, B., Mulugetta, Y., 2018. Mapping synergies and trade-offs between energy and the sustainable development goals. Nat. Energy 3 (1), 10–15. https://doi.org/10.1038/s41560-017-0036-5.
Fuso Nerini, F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., Tavoni, M., Tomei, J., Zerriffi, H., Milligan, B., 2019. Connecting climate action with other sustainable development goals. Nature Sustain. 2 (8), 674–680. https://doi.org/10.1038/s41893-019-0334-y.
Giampietro, M., Mayumi, K., Munda, G., 2006. Integrated assessment and energy analysis: quality assurance in multi-criteria analysis of sustain- ability. Energy 31 (1), 59–86. https://doi.org/10.1016/j.energy.2005.03.005.
Google Timelapse, Our Ocean, 1984–2020, Google Earth, 2021.
Greene, C.A., Thirumalai, K., Kearney, K.A., Delgado, J.M., Schwanghart, W., Wolfenbarger, N.S., Thyng, K.M., Gwyther, D.E., Gardner, A.S., Blankenship, D.D., 2019. The climate data toolbox for matlab. Geochem. Geophys. Geosyst. 20 (7), 3774–3781. https://doi.org/10.1029/2019GC008392.
Hagens, N., 2020. Economics for the future – beyond the superorganism. Ecol. Econ. 169, 106520 https://doi.org/10.1016/j.ecolecon. 2019.106520.
Hák, T., Janoušková, S., Moldan, B., 2016. Sustainable development goals: a need for relevant indicators. Ecol. Indic. 60, 565–573. https://doi.org/10.1016/j.ecolind.2015.08.003.
Hezri, A.A., Dovers, S.R., 2006. Sustainability indicators, policy and governance: issues for ecological economics. Ecol. Econ. 60 (1), 86–99. https://doi.org/10.1016/j.ecolecon.2005.11.019.
Hickel, J., 2020. The sustainable development index: measuring the ecological efficiency of human development in the anthropocene. Ecol. Econ. 167, 106331 https://doi.org/10.1016/j.ecolecon.2019.05.011.
Houghton, R.A., Nassikas, A.A., 2017. Global and regional fluxes of carbon from land use and land cover change 1850–2015. Glob. Biogeochem. Cycles 31 (3), 456–472. https://doi.org/10.1002/2016GB005546.
Hsu, A., Zomer, A., 2016. Environmental Performance Index, in: Wiley StatsRef: Statistics Reference Online. John Wiley & Sons, Ltd, pp. 1–5. https://doi.org/10.1002/9781118445112.stat03789.pub2.
Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grübler, A., Huntley, B., Jäger, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore, B., O'Riordan, T., Svedin, U., 2001. Sustainability science. Science 292 (5517), 641–642. https://doi.org/10.1126/science.1059386.
Lettenmeier, M., Liedtke, C., Rohn, H., 2014. Eight tons of material footprint-suggestion for a resource cap for household consumption in Finland. Resources 3 (3), 488–515. https://doi.org/10.3390/resources3030488.
Lindsay, A.R., Sanchirico, J.N., Gilliland, T.E., Ambo-Rappe, R., Taylor, J.E., Krueck, N. C., Mumby, P.J., 2020. Evaluating sustainable development policies in rural coastal economies. Proc. Natl. Acad. Sci. U. S. A. 117 https://doi.org/10.1073/pnas.2017835117.
Lucia, U., Grisolia, G., 2021. The gouy-stodola theorem—from irreversibility to sustainability—the thermodynamic human development index. Sustainability 13. https://doi.org/10.3390/su13073995.
Moldan, B., Janoušková, S., Hák, T., 2012. How to understand and measure environmental sustainability: indicators and targets. Ecol. Indic. 17, 4–13. https://doi.org/10.1016/j.ecolind.2011.04.033.
Morse, S., McNamara, N., Acholo, M., Okwoli, B., 2001. Sustainability indicators: the problem of integration. Sustain. Dev. 9 (1), 1–15. https://doi.org/10.1002/sd.148.
Nilashi, M., Rupani, P.F., Rupani, M.M., Kamyab, H., Shao, W., Ahmadi, H., Rashid, T.A., Aljojo, N., 2019. Measuring sustainability through ecological sustainability and human sustainability: a machine learning approach. J. Clean. Prod. 240, 118162 https://doi.org/10.1016/j.jclepro.2019.118162.
Nourry, M., 2008. Measuring sustainable development: some empirical evidence for France from eight alternative indicators. Ecol. Econ. 67, 441–456. https://doi.org/10.1016/j.ecolecon.2007.12.019.
Ozturk, I., 2015. Sustainability in the food-energy-water nexus: evidence from brics (Brazil, the Russian Federation, India, China, and South Africa) countries. Energy 93, 999–1010. https://doi.org/10.1016/j.energy.2015.09.104.

Patzek, T.W., 2004. Thermodynamics of the corn-ethanol biofuel cycle. Crit. Rev. Plant Sci. 23 (6), 519–567.

Patzek, T.W., 2007. How can we outlive our way of life?. In: 20th Round Table on Sustainable Development of Biofuels: Is the Cure Worse than the Disease? OECD, Paris, pp. 1–49. http://www.oecd.org/sd-roundtable/papersandpublications/40225820.pdf.

Patzek, T.W., Pimentel, D., 2005. Thermodynamics of energy production from biomass. Crit. Rev. Plant Sci. 24 (5–6), 329–364.

Peters, C.J., Wilkins, J.L., Fick, G.W., 2007. Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: the New York state example. Renew. Agric. Food Syst. 22 (2), 145–153. https://doi.org/10.1017/S1742170507001767.

Ram, M., Aghahosseini, A., Breyer, C., 2020. Job creation during the global energy transition towards 100% renewable power system by 2050. Technol. Forecast. Soc. Chang. 151, 119682 https://doi.org/10.1016/j.techfore.2019.06.008.

Raven, P.H., Wagner, D.L., 2021. Agricultural intensification and climate change are rapidly decreasing insect biodiversity. Proc. Natl. Acad. Sci. 118 https://doi.org/10.1073/pnas.2002548117.

Reed, M.S., Fraser, E.D., Dougill, A.J., 2006. An adaptive learning process for developing and applying sustainability indicators with local com- munities. Ecol. Econ. 59, 406–418. https://doi.org/10.1016/j.ecolecon.2005.11.008.

Rees, W.E., 1992. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environ. Urban. 4 https://doi.org/10.1177/095624789200400212.

Rees, W.E., 2010. What's blocking sustainability? Hum. Nat. Cogn. Denial Sustain. 6 (2), 13–25. https://doi.org/10.1080/15487733.2010.11908046.

Rees, W.E., 2020. Ecological economics for humanity's plague phase. Ecol. Econ. 169, 106519 https://doi.org/10.1016/j.ecolecon. 2019.106519.

Ricke, K.L., Caldeira, K., 2014. Maximum warming occurs about one decade after a carbon dioxide emission. Environ. Res. Lett. 9 (12), 124002 https://doi.org/10.1088/1748-9326/9/12/124002.

Riekhof, M.C., Regnier, E., Quaas, M.F., 2019. Economic growth, international trade, and the depletion or conservation of renewable natural resources. J. Environ. Econ. Manag. 97, 116–133. https://doi.org/10.1016/j.jeem.2018.04.008.

Ripple, W.J., Wolf, C., Newsome, T.M., Galetti, M., Alamgir, M., Crist, E., Mahmoud, M. I., Laurance, W.F., 2017. World scientists' warning to humanity: A second notice. BioScience 67 (12), 1026–1028. https://doi.org/10.1093/biosci/bix125.

Ritchie, H., 2007. How Much of the world's Land Would we Need in Order to Feed the Global Population with the Average Diet of a Given Country? - our World in Data.

Ritchie, H., Roser, M., 2020. Co2 and Greenhouse Gas Emissions, Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas- emissions.

Roche, K.R., Müller-Itten, M., Dralle, D.N., Bolster, D., Müller, M.F., 2020. Climate change and the opportunity cost of conflict. Proc. Natl. Acad. Sci. 117 https://doi.org/10.1073/pnas.1914829117.

Rockström, J., Steffen, W., Noone, K., Åsa Persson, F.S., Chapin, E., Lambin, T.M., Lenton, M., Scheffer, C., Folke, H.J., Schellnhuber, B., Nykvist, C.A.D., Wit, T., Hughes, S.V.D., Leeuw, H., Rodhe, S., Sörlin, P.K., Snyder, R., Costanza, U., Svedin, M., Falkenmark, L., Karlberg, R.W., Corell, V.J., Fabry, J., Hansen, B. Walker, 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14.

Rowley, H.V., Peters, G.M., Lundie, S., Moore, S.J., 2012. Aggregating sustainability indicators: beyond the weighted sum. J. Environ. Manag. 111, 24–33. https://doi.org/10.1016/j.jenvman.2012.05.004.

Seibert, M.K., Rees, W.E., 2021. Through the eye of a needle: an eco-heterodox perspective on the renewable energy transition. Energies 14 (15). https://doi.org/10.3390/en14154508.

Statistics Times, 2018. Gdp (Nominal) vs gdp (ppp).

Stiglitz, J., 2020. Gdp is the wrong tool for measuring what matters. Sci. Am. 323 (2), 24–31.

Stokstad, E., 2020. Deep deficit. Science 368 (6488), 230–233. https://doi.org/10.1126/science.368.6488.230.

Thaler, E.A., Larsen, I.J., Yu, Q., 2021. The extent of soil loss across the us corn belt. PNAS 118 (8). https://doi.org/10.1073/pnas.1922375118.

Tiseo, I., 2020. Global Waste Generation - Statistics & Facts, Statista. Nov.

Toth, G., Szigeti, C., 2016. The historical ecological footprint: from over-population to over-consumption. Ecol. Indic. 60, 283–291. https://doi.org/10.1016/j.ecolind.2015.06.040.

UN, 2018. Human Development Index (HDI) — Human Development Reports.

UN, 2020. Global Material Flows Database — Resource Panel.

UNDP, 2021. Human Development Reports. http://hdr.undp.org/en/indicators/137506.

Valentin, A., Spangenberg, J.H., 2000. A guide to community sustainability indicators. Environ. Impact Assess. Rev. 20 (3), 381–392. https://doi.org/10.1016/S0195-9255(00)00049-4.

Wackernagel, M., 1994. Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning toward Sustainability. Ph.D. thesis. University of British Columbia. https://doi.org/10.14288/1.0088048.

WBGU, 2009. Solving the Climate Dilemma: The Budget Approach, Tech. Rep. WBGU.

Wheeler, T., von Braun, J., 2013. Climate change impacts on global food security. Science 341. https://doi.org/10.1126/science.1239402.

Zhang, X., Caldeira, K., 2015. Time scales and ratios of climate forcing due to thermal versus carbon dioxide emissions from fossil fuels. Geo- Phys. Res. Lett. 42 (11), 4548–4555 arXiv:https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015GL063514. https://doi.org/10.1002/2015GL063514. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015GL063514.