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A framework for quantifying environmental sustainability

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ABSTRACT

Recent concepts of environmental sustainability have focused on narrative economic and societal aspects rather than quantitative ones. Many key sustainability indicators also lack a consistent definition of sustainability, have perspectives that are too short-term, and are unable to model the dynamics of complex environmental utilization which can then result in inappropriate projection of long-term sustainability and/or sustainability indication. Here I propose a generalized quantitative framework of environmental sustainability requiring that (1) environmental capacities and utilization rates are identified, (2) their complex temporal dynamics are quantitatively modeled or estimated (3) while also adjusting for uncertainties, and finally, (4) using one of three options, determining which cumulative utilization pathways can be sustained for a (usually well-defined) period of time. Using the example of wood volume and its growth as capacities and harvest as utilization, and the example of global greenhouse gas emissions as the utilization component and the capacity of the air to absorb these emissions, I demonstrate how the proposed framework can be applied in practice, how sustainability indicators could be developed, and also how they can inform policies and measures to ensure sustainability.

1. Introduction

One of the first documented applications of sustainability as a concept grew out of the need to address a timber shortage crisis in medieval Europe. To manage this crisis, Carlowitz (1713) developed the idea that the ever stronger scarcity of timber can be avoided by ". . . the careful management of sustainable forestry resources". This idea involved two complimentary concepts that gradually became standard in forestry. One is that the management should include "the natural growing of wild trees, . . . sowing, growing and planting of seedlings" as well as "the preparation of soil for sowing and the care of seedlings" (Carlowitz, 1713). The other concept, called sustained yield, is a quantitative one: "Sustained yield management of wood . . . would, in technical terms, be considered to be achieved if the total harvest does not exceed the accumulated annual increment during a specified planning period" (FAO, 1998). It is generally implemented by requiring that the value of standard forestry statistics such as forest area, standing volume, woody increment and forest biomass carbon stocks should increase, or at least they are not supposed to decrease (e.g. Somogyi and Zamolodchikov, 2007). A similar concept has also been applied in fishery for eight decades (Russell, 1931), and was generalized by Daly (1990) who stated that with renewable capacities, harvest rates should equal regeneration rates.

After the idea of "sustainable development" by the Brundtland Commission (WCED, 1987) was published, "sustainability" was redefined less quantitatively and applied more generally to address many emerging environmental issues. The concept stated that the ability of future generations to meet their own needs should not be compromised by the consumption of the present generation. However, neither future needs nor current consumption were defined explicitly, let alone quantitatively, and it was not defined, either, why and how consumption should be limited. Although the need for such limitations had been evident at the global level for some time (Meadows et al., 1972), the concept did not recognize, either, that consumption and limitations are characteristics of complex dynamic systems.

The shortcomings of the definition became evident soon, and were amended by including a reference to the need to live "within the carrying capacity of supporting ecosystems" (IUCN UNEP WWF, 1991), but only in the context of "ecosystems", and not environmental resources (both biotic and abiotic) in a broad sense. Further developments and new definitions led to the situation that, according to Marshall and Toffel (2005), "there were well over 100 definitions of sustainability" by the mid-1990s, all "open to interpretation", and such a "definitional chaos has nearly rendered the term sustainability meaningless and is distracting from the need to address ongoing environmental degradation" (Holling, 2000).

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One of the reasons for this chaos was that the concept was extended for too many issues beyond quantitative ones. For example, Costanza and Patten (1995) applied it not only to human sustainability on Earth but also to many non-sustainability-related situations and contexts over different scales of space and time. The Earth Charter Initiative (Earth Council, 2000) envisioned "a sustainable global society founded on respect for nature, universal human rights, economic justice, and a culture of peace." Porritt (2005) and others believed that sustainable development is rather a social and economic project with the objective of optimizing human well-being, thus again preventing the development of the concept from establishing its foundations on natural laws. Milne et al. (2006) talk about sustainability as a call for action, a task in progress, a political process, a "journey". Further, probably unnecessary complexity was added by economists (see e.g., Costanza and Daly, 1992) who talk about "weak sustainability" (which assumes that the depletion of natural capacities can be compensated by investing in human-made capital) and "strong sustainability" (saying that natural capital and man-made capital should be maintained separately).

Some approaches better acknowledge the quantitative nature of the relationship between the allowable levels of environmental utilization and available capacities, for example, The Limits to Growth model by Meadows et al. (1972) that extended the concept of limitations to global population growth. More often, however, such a relationship has often been implicitly applied, i.e., without introducing any quantitative formula. Historical examples of this concept include Carson's (2002) "Silent Spring" of 1962 that stated that the natural assimilative capacities of the ecosystems to absorb chemical pesticides (such as DDT) are limited.

The more recent concept of "planetary boundaries" by Rockström et al. (2009) explicitly links sustainability to the idea that such boundaries (i.e. limits of our use of the planetary environment) exist, that they can be identified one way or another, that they should be respected, and that policies of governance and management can be developed so that these boundaries are not transgressed. Such boundaries are not placed exactly at biophysical thresholds or tipping points for anthropogenic perturbation of critical Earth System processes, rather, somewhere at the end of a "safe operating space", i.e., well before reaching these thresholds. While this approach allows for uncertainties and time for society to react to early warning signs that it may be approaching a threshold and consequent abrupt or risky change (Steffen et al., 2015), the application of such boundaries, i.e., rather static levels or rates, is inevitably a simplification of the dynamics of a complex system that includes both the biophysical characteristics of the Earth and the human society, and excludes a proper consideration of the time dimension (e.g., for how long a perturbation may be outside of a "safe zone" without jeopardizing sustainability).

Currently, there is no comprehensive and universally agreed non-narrative definition of sustainability. Some relevant recent UN documents (such as the outcome of the Rio + 20 conference in 2012, "The Future We Want", 2012) actually avoid defining the term sustainability. Instead, they include non-operative sentences like "the long-term vision of the high-level panel on global sustainability is to eradicate poverty, reduce inequality and make growth inclusive, and production and consumption more sustainable, while combating climate change and respecting a range of other planetary boundaries" (UN, 2012). Many scientific publications (e.g., Steffen et al., 2004) also use "sustainability" without a definition, as if the concept were clear.

As a parallel process to the above, sustainability has been indirectly defined by attempts to "measure" it in one way or another. One promising recent effort is called ecosystem accounting (Hein et al., 2015), however, among others, it focuses on ecosystems (excluding some abiotic elements of the environment), and limits sustainability to specific situations when there is a (short-term) balance between the actual use and the capacity of an ecosystem (Schröter et al., 2014), without considering long-term system dynamics.

Currently, a more common method is to use indicators both in sustainability science and practice (Singh et al., 2009), however, without any universally applicable approach how to develop them. Indicator systems, such as that of Forest Europe (2011), which is widely applied for the management of vast areas of forests in Europe and Russia, often lack a coherent conceptual framework (Grainger, 2012; EFI, 2013), and only accumulate information with little conceptual foundation (Wijewardana, 2008). Generalizing the conclusion of the recent analysis of Forest Europe (2011) by EFI (2013), these systems may thus be "in need of revision".

Here I argue that such revisions should include re-defining sustainability in a quantitative framework, based on the law of the conservation of mass and energy. First, I propose a generalized quantitative definition of environmental sustainability. Then I show, using three systems of widely applied forest-related indicator systems as examples, why inappropriately defined indicators can provide biased assessment of sustainability. To demonstrate how the proposed definition of environmental sustainability could be applied in practice, two examples are shown. Finally, I discuss how sustainability indication might be developed in the future based on the proposed approach.

2. Methods

2.1. The definition of quantitative environmental sustainability

In the below *quantitative concept of environmental sustainability* I assume that, for any system with specific physical and chemical properties and particular natural laws, both the anthropogenic use of environmental resources, i.e., utilization, and the amount of all of these resources, i.e., capacity, can be classified into one of the quantities in Box 1, and measured using the same physical units (e.g., mass, volume, energy content, etc.).

The utilization and related capacity changes are modeled in what are referred to here as rounds. One round can last either until one unit of capacity, defined in applications as practicable, is used

Box 1: Definitions required for the application of the generalized environmental sustainability. See text for details.

Utilization, U = the rate of the use of capacities in terms of mass or energy (e.g. wood harvesting). It can include components that may affect renewable and non-renewable capacities.

Environmental capacity, C = the amount of mass or energy (e.g., standing volume) that is available in, or that (e.g., in the form of greenhouse gas emissions) can be absorbed by, the environment.

Initial capacity, C_0 = the amount of the capacity (e.g., the amount of harvestable wood in forests) at the beginning of the analysis.

Renewed capacity, C_{ren} = the amount of the capacity that is renewed, after or simultaneously with utilization or capacity loss, due to natural (e.g., wood growth) or humand-induced processes (e.g., by forest regeneration).

Extended capacity, C_e = any (non-utilization related) capacity that is established by additional investment (e.g., by increasing wood growth capacities by afforestations) or natural processes (e.g., natural forest expansion).

Lost capacity, C_l = any (non-utilization related) loss of capacities (in any of the above categories) due to natural or human causes (e.g., loss of forests due to natural catastrophes).

up (e.g., one round can last until all energy is retrieved from one load of fuel in an atomic power plant or in a car), or for one unit of time (e.g., one year).

Assume that the available capacity in round **1**, before the first utilization in the analysis, C_1 is:

$$C_1 = C_0 + C_{\text{ren}1} + C_{\text{e}1} - C_{\text{l}1} \quad (1)$$

Utilization in the first round, U_1, can only take place if

$$U_1 \le C_1 \quad (2)$$

The amount of capacity available for utilization in round 2 (again, after all non-utilization related changes in the capacities, but before utilization in the round) is:

$$C_2 = C_1 - U_1 + C_{\text{ren}2} + C_{\text{e}2} - C_{\text{l}2} \quad (3)$$

Extending the above to round r, and assuming that utilization is always possible in the previous rounds, C_r can be calculated the following way:

$$C_r = C_0 + \sum C_{\text{ren}r} + \sum C_{\text{e}r} - \sum C_{1r} - \sum U_{r-1} \quad (4)$$

where summations are done from 1 to $\boldsymbol{r}$ for the capacities and $r-1$ for the utilization rates. In round $\boldsymbol{r}$, utilization is possible if

$$U_r \le C_r \quad (5)$$

Based on the above, the proposed quantitative definition of sustainability is as follows: The utilization of the capacities is sustainable for a maximum number of R rounds for which Eq. (5) holds true for each and every round $r = 1,\ldots,R$. (Note that, in addition to the above requirement, U_r may also need to be limited by system-specific, non-capacity related thresholds or other system requirements in any round. However, for the purposes of the below analysis, it is assumed that no such additional limitations exist.)

An important feature of the above definition is that, for any year r, U_r, i.e., the utilization rate in a specific round, is not limited by the amount of capacity changes in that single round, rather, by the available capacities that are the sum of the initial capacities and all previous capacity changes and utilizations. Thus, comparing utilization in a round, U_r, with capacity changes specific to that single round r, which is often the case with indicators (see below), is an inappropriate measure of sustainability.

The above definition allows that the amount of U, C_{ren}, C_{e} and C_{l} can all change from round to round, and thus allows for the dynamics of utilization rates and capacity development as long as, for any rounds $1,\ldots,r$, the total utilization does not exceed the total of all available capacities and capacity changes:

$$\sum U_r \le C_0 + \sum C_{\text{ren}r} + \sum C_{\text{e}r} - \sum C_{\text{l}r} \quad (6)$$

2.2. Sustainability assessment using the proposed definition of sustainability

The above definition offers a way to quantitatively analyze if the utilization of an environmental system is sustainable or not for any period of time. This analysis involves the following four steps.

(1) Identify appropriate capacities and related utilization

The elements of the environment to sustain (e.g., the volume or growth of forests) can often be directly related to the utilized quantities (e.g., the amount of harvest). In some cases, however, environmental variables to be sustained within specific limits (e.g., air temperature) are different from those that are directly affected by human activities (e.g., greenhouse gas emissions; see also the below demonstration). In order that sustainability can be analyzed and implemented, both groups of variables should be clearly identified.

(2) Estimate quantities of capacity and utilization

The quantification of the variables in Eqs. (1)–(5) is system-specific, and may depend on whether the analysis is done for the past (e.g., using historical data) or future utilization (using assumptions and model projections, often by various scenarios).

(3) Adjust for uncertainties and risks

An important fact of environmental assessment and monitoring is that, mainly due to the dimensions, time-scale and complex nature of ecological systems, the estimation and projection of key environmental variables usually involve rather high uncertainties. For example, rather high uncertainties of emissions and removals are routinely reported for the land use sector in annual greenhouse gas inventories (available at http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/6598.php). Also, the implementation of environmental sustainability policies may unintendedly fall short of planned harmonization of utilization rates with capacities, which entails risks of violating sustainability. Of the several possible ways to deal with these uncertainties and risks, two are presented here. One approach, a general practice in engineering, involves the application of a factor of safety, i.e., utilization rates are increased and/or capacities are reduced by specific factors. The other approach applies conservativeness, a commonly used concept, e.g. in implementing the sustain yield concept and in greenhouse gas inventories, which can be used if the range of uncertainties is known. In such cases the upper endpoint of the estimated confidence interval of utilization and the lower endpoint of the estimated confidence interval of capacities are used in calculations.

The variables applied in the formulas of the below final step of the analysis are assumed to have been appropriately adjusted by using one of the above approaches.

(4) Assess sustainability

Sustainability as defined above can be assessed in three different ways:

- *Option A*: If C and U trajectories are known, then the resulting R should be checked if it is large enough compared with what is required. If, e.g., we know (or assume) how large fossil fuel reserves are available on Earth, and how much fossil fuels we need annually until, in X years from now, energy-producing new technologies (e.g., based on renewables) can take over, then we can calculate the number of years, R, until the stocks will last, and check if $R \ge X$.
- *Option B*: If C trajectories and the required amount of R are known, then it should be checked if there is at least one acceptable U trajectory for which Eq. (5) holds true for all R rounds. If, e.g., we know how much the capacity of the air is to take up carbon-dioxide, and assume that emissions can be reduced to near-zero values in, say, $X = 50$ years, then the total amount of emissions, $\sum_r U_r$, can be calculated, from which trajectories of annual emissions can be developed. If at least one of these trajectories can be implemented to always satisfy Eq. (5), then, and only then, can emissions be deemed sustainable.
- *Option C*: If the trajectory of U can be assumed for a period of R, then the calculated capacities that are required to allow for the utilization must not exceed the existing ones. If, e.g., for a maximum of a specified number of years R, a country requires a certain rate of annual deforestations, U, to create cropland that it

needs for its development until its agricultural sector is developed enough to meet demands for food and other means of industrial production on a constant area basis, then it can be checked if the area of current and newly established forests will be enough for *R* years to meet demands for the deforestations or not.

3. An analysis of some sustainability indicators based on the proposed sustainability framework

Below, some indicators of three forest-related systems of sustainability indicators as examples are tested against the proposed sustainability definition to demonstrate that many indicators are inappropriate measures of sustainability.

The *European system of criteria and indicators for forests and forestry* (in short, ESCI, Forest Europe UNECE and FAO, 2011) includes 35 quantitative indicators. These are usually not directly linked to any utilization rates or capacities, rather, they are only used as proxies or simple indications of whether specific information is available in countries or not. That some indicators fail to demonstrate how their values are to be assessed for sustainability (Somogyi, 1994) is acknowledged by the system itself by saying that "it is hard to interpret the raw data", "insufficient knowledge is available to estimate what are 'desirable' deadwood levels" or some indicators are deemed "a weak indicator of sustainability". In a specific case, it is "implicitly assume[d] that increase in forest area is positive", but it is not clear why an increase of the area of an undefined "forest" is in itself seen as positive. The area can increase in many forms (e.g. through the spreading of invasive tree species) and in many places (even in undesirable ones) that may be regarded as negative.

In other cases, the applied theory is flawed. For example, using data for a period of few years, every value of the "ratio of felling and net annual increment under 95 percent is considered equally acceptable" (the "95 percent is chosen to take account of harvesting losses, etc. and as a measure of prudence"). However, it is well known in forestry that both wood harvest and forest growth can substantially vary from period to period if they are short ones (among others, due to economic reasons and variations in weather conditions, respectively) but wood harvesting can remain sustainable as long as the total harvests do not exceed total stand growth in the long run. Therefore, the above ratio can easily take values larger than 100 in the short run without any threat to sustainability if, during the same and other periods, the growing stock can provide enough volume for the harvests.

The indicator "Percentage of natural ecosystem area at risk of eutrophication for an emission scenario based on current legislation" is "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge". It is thus based on the concept of critical loads which is the maximum quantifiable flux that an ecosystem is able to sustain (Hettelingh et al., 2001; EEA, 2003). While useful in specific situations, this concept, such as the idea of "environmental limits" and "planetary boundaries", is only able to consider some aspects of dynamic systems, and lacks the full perspective of the proposed concept of sustainability as suggested above.

Finally, some indicator values can be easily misinterpreted. Such an indicator is the "Percent of forest area damaged by biotic, abiotic and human-induced causes/percent damaged by fire" which may be deemed as "positive" if it is declining over time. However, such a decline can lead to consequences with adverse effects on sustainability. An instructive example is the case of forest fires in the Yellowstone National Park where forest fires, which are natural elements of forest ecosystems, were regarded as a destructive force for decades. In fact, the area damaged by forests decreased in the Park due to fire suppression for a long time but, in lack of fires, deadwood fuel started to accumulate, eventually resulting in the largest wildfire in the recorded history of the Park in 1988 (Franke, 2000). The decrease of forest area damaged by fire is just a proxy for the ultimately required environmental property to be kept within limits, i.e. the amount of deadwood fuel, and is a way too simplistic model of a complex phenomenon, therefore, it is an inappropriate sustainability indicator.

The *Environmental Performance Index* (EPI, Emerson et al., 2012) is a suite of indicators, applied for a number of countries on a quantitative basis, to track environmental results for the past few years. The national EPI indicators are also intended to measure how far countries are from "targets" and/or relative to each other in reaching these targets.

One of the indicators of the EPI system is the change in forest area between five-year-long periods of time penalizing countries that are losing forest cover. Between 1990 and 2010, Brazil lost some 9.6% of its forests (a total area the size of France, FAO, 2010), and such a loss in consecutive five-year periods is considered negative with respect to sustainability. In contrast, the Ecological Footprint reports for Brazil in 2010 a high bio-capacity of 6.67 global hectares per capita (a high positive value) and a much smaller forestry footprint of 0.57 global hectares per capita (Global Footprint Network, 2012), suggesting a high ratio of the two values and thus a positive forestry index. The contradiction of the two indicators demonstrate that, unless short-term values are put in the long-term perspective of systems dynamics, they cannot be conclusive with respect to sustainability.

The same applies to the ratio of "the total growing stock in a later period" and "the growing stock in the prior period" of the EPI system where "a ratio of >=1 means that the growing stock has remained unchanged or is growing, and a ratio of <1 means that the growing stock is being depleted." "The target is zero change. This is consistent with the logic that 'cutting forests faster than their rate of regrowth is an unsustainable and environmentally harmful policy"' (Emerson et al., 2012). This definition, too, excludes any consideration of the temporal variability of tree growth and harvests, which may be quite large for short periods as mentioned above, and even if harvests are larger than tree growth for some time, it is possible that forest management is sustainable if total harvests do not exceed the total tree growth in the long term.

Finally, if the above ratio of growing stocks is 0.9 for one country and 0.95 for another one, it does not necessarily mean that the former is farther from sustainability. In each country, all depends on temporal patterns of harvests and tree growth, i.e. utilization and capacity, which may in turn depend a lot on local age class distribution legacy and other factors.

The *Ecological Footprint* (Rees, 1992; Wackernagel, 1991) is a set of indicators that are meant to assess sustainability by relating footprints, i.e., the amount of resources a human population requires, to available natural capacities. According to Borucke et al. (2013), the Ecological Footprint is "a measure of the demand populations and activities place on the biosphere in a given year, given the prevailing technology and resource management of that year" (emphasis added). Thus, by its very design, this set of indicators does not consider temporal dynamics.

More specifically, the "Carbon Footprint" (EF_C) is calculated using the following formula (Borucke et al., 2013):

$$EF_C = P_C * (1 - S_{Ocean})/Y_C * EQF \quad (7)$$

where (using appropriate units, and with emphasis added), P_C = the annual anthropogenic emissions of carbon dioxide, S_{Ocean} = the fraction of anthropogenic emissions sequestered by oceans in a given year, Y_C = the annual rate of carbon uptake per hectare of world average forest land, calculated from net biomass growth values reported by IPCC (2006), and *EQF* = an equivalence factor

allowing results to be expressed in terms of a standardized unit of measure.

This indicator is flawed for several reasons, and not only for those raised by Blomqvist et al. (2013). First, the real capacity of forests to sequester carbon is not equal to Y_C, i.e., net biomass growth, rather, it is the resultant of net biomass growth (gains) and the sum of emissions from harvests, natural disturbances and the decay of dead wood (losses). The value of this real capacity is usually much smaller than the net biomass growth (for Europe, for example, the respective annual values are about 662 million m^3 and 1552 million m^3, Forest Europe UNECE and FAO, 2011). This can also be easily shown by the following calculation: given that the current (2013) net of carbon gains and carbon losses of all land is about 25%, and the fraction of anthropogenic emissions sequestered by oceans is about 29% of all anthropogenic emissions (about 9.9 $GtCyr^{-1}$, Global Carbon Budget, 2014), the Carbon Footprint formula would result in a global footprint/biocapacity ratio of 2.8, which is much larger than any meaningful value.

Second, the carbon uptake of forests is rather variable. This variability is due to the variability of both the gains and the losses. The net of these can be positive or negative in the short run. For example, dry years in 2005 and 2010 easily turned earlier removals into emissions in the natural Amazonian rainforests (Lewis et al., 2011). In fact, however, forests (especially on large areas) tend to be close to dynamic carbon equilibrium over the long run because biomass growth is mostly offset by losses due to harvests and natural disturbance. This is also evident from carbon models and data reported in greenhouse gas inventories (e.g., Canada, 2012). An indicator with zero net uptake makes no sense.

Finally, as shown earlier, and within limits, high annual variations of footprint values may have nothing to do with long-term sustainability. What matters for sustainability is the amount cumulative emissions relative to the absorbing capacity of the climatic system in the long run. Because of all the above, the widely used Carbon Footprint is an inappropriate measure of the sustainability of human activity with respect to climate change.

In conclusion, many indicators have only created the illusion of being able to measure sustainability, but in fact they are poor metrics of a concept that has not been sufficiently well defined, either.

4. Discussion

As the review of recent environmental sustainability concepts demonstrated, they mainly or exclusively involve narrative elements, and thus only represent an intention or hope, rather than analytical tools, to maintain (in an undefined manner and to an unquantified extent) the capabilities of the environment in general to meet human needs (also undefined) in future (i.e. until an undefined point in time). Very often, indicators are not even quantitative ones and, in lack of sufficient proof, it is not clear whether they can determine if a system can be sustained or not (e.g., EFI, 2013). Some of them have been recently criticized, e.g., the Ecological Footprint: “EF measurements, as currently constructed and presented, are so misleading as to preclude their use in any serious science or policy context” (Blomqvist et al., 2013), yet, for example the EFs in general, are still widely used, while others (e.g., the so-called Waste Absorption Footprint, Wenjun et al., 2015) have even more recently been proposed.

Improving on these indicators should consider that environmental capacities, including those available as ecosystem services, are physical entities that can only be analyzed by considering quantitative variables and applying the law of the conservation of mass and energy to them. Just like in the case of the centuries-old concept of sustained yield in forestry or other engineering type of approaches do (e.g., Neuman and Churchill, 2011), the proposed sustainability framework meets this requirement.

It is, however, clearly not enough to define “indicators” as a quantitative and measurable variable representing an operational attribute of a given system (Gallopin, 1997). For example, due to simplifications, concepts like the that of planetary boundaries might prove to be insufficient: even the advocates of this concept themselves acknowledge that identifying critical planetary boundaries provides only one important element that can inform society's decisions about sustainability (Rockström et al., 2009). As demonstrated by analyzing some indicators (e.g., forest area of the EPI system and the Carbon Footprint), easily available statistics or their ratios may, too, oversimplify complex system dynamics of utilization and/or available capacities. However, including more than just a series of annual data for a longer time period may not suffice, either. Consider a more correct carbon footprint, EF_C', in following form:

$$EF_C' = \sum P_C / \left(\sum S_O + \sum Y_C' \right) * \mathrm{EQF} \quad (8)$$

where, for a series of years for which the summations ($\sum$) are done, S_O = the annual amount of anthropogenic emissions sequestered by oceans, Y_C' = the annual net carbon gain or loss of forests.

Formula (8) (which is similar to Eq. (6)) still provides for a too simplistic analysis because in addition to requiring that utilization meets the requirements of Eq. (6), sustainability requires that Eq. (5) holds true, too. Calculating the above ratio essentially takes the average of the annual values, and information on their dynamics, and the associated flexibility which might be important for long-term sustainability, are lost. In contrast, assessing sustainability based on the above steps (1)–(4) allows for these dynamics and provides sufficient basis for a thorough and flexible temporal analysis of the utilization.

To demonstrate the general applicability of the proposed concept of sustainability and its possible use in sustainability indication in practice, two examples are provided below. One is concerned with the utilization of a (hypothetical) forest with C_0 = 39,000 thousand m^3 and values of C_{ren}, C_e, C_l and U over a period of 10 rounds (or years) vary as reported in Table 1. As the total net addition to the capacities (i.e., $C_{ren} + C_e - C_l$) is slightly larger than the total utilization for the entire period the utilization during the period analyzed can be deemed sustainable, even without exploiting any of the starting capacities. However, the numbers also demonstrate that, contrary to what the EPI and the Ecological Footprint systems suggest, in specific years, and under specific conditions, utilization can deviate to some extent from some measures of capacity without jeopardizing sustainability: capacities can decrease (it happened 5 out of 10 times); utilization can be more than either the annual or the long-term average net addition to the capacities; and the annual footprint indicator value (calculated as the ratio of utilization and the total net addition to the capacities) can be larger (or much larger) than 1 (Table 1). Footprint values calculated even from five-year totals can be misleading: the value of such a footprint for years 1–5 is 1.10, i.e., it is also quite different from 1 which is the maximum for long-term sustainability, yet, the utilization of the forest is sustainable, clearly demonstrating situations in which the application of the EPI and footprint-type indicators may not be useful in assessing sustainability. Note, however, that the footprint calculated for the entire period, i.e., 0.91, demonstrates that utilization is sustainable *for the period analysed*. Note also that taking 1 as the maximum footprint value for long-term sustainability may not be justified because of rarely happening but very large disturbances of the system (see the large loss in round 8) that might reduce capacities beyond their assumed rate, which calls for the consideration of uncertainties (see the second example below).

Table 1
Capacities and utilization of a forest (symbols are as in Eqs. (1)–(6), and numbers are in thousand m^3 wood volume), and a footprint-type indicator (as defined in the last two columns) over a period of 10 rounds (or years). Years are highlighted in the respective columns when: capacities decrease from the previous year (in bold and italic); utilization is larger than annual net capacity addition (in bold), its long-term average (in italic), or both (in bold and italic); and a footprint-type indicator is higher than 1 (in bold). Notes: (1) the numbers are hypothetical but realistic; (2) the numbers and calculations only consider sustainability in terms of tree volume, irrespective of the nature of trees harvested with regard to age, species or other features that might be subject to similar but more detailed analyses of sustainability.

Round	C	C_{ren}	C_e	C_l	$C_{ren} + C_e - C_l$	U	Footprint = $U/(C_{ren} + C_e - C_l)$ from	
							Annual values	Five-year totals
1	40,000	1000	3	3	1000	*998*	0.75	
2	40,285	1339	4	60	1337	881	0.66	
3	***40,232***	835	3	10	837	**947**	**1.13**	
4	***39,982***	719	3	25	720	***1043***	**1.45**	
5	***39,507***	576	4	12	578	***1040***	**1.80**	**1.10**
6	***39,433***	997	3	34	997	753	1.00	**1.04**
7	40,177	1499	4	5	1502	898	0.60	**1.01**
8	40,246	1413	4	***450***	1372	589	0.43	0.84
9	40,393	802	4	70	798	**823**	**1.03**	0.78
10	***40,346***	786	4	14	788	***1029***	**1.31**	**0.75**
Mean		**997**	**4**	**68**	**993**	**900**		

The second example, in which a simplified analysis is presented concerning the sustainability of CO_2 emissions as utilization in relation to the capacity of the air to absorb these emissions, demonstrates how longer-term sustainability can be assessed according to the step-by-step procedure of the proposed framework. The analysis is done in a time-scale deemed relevant for mitigating climate change, i.e., until 2100. For the purposes of the demonstration, the most recent scientific results are generally applied, but also a number of non-explicit assumptions and simplifications that, together with the values used, should be replaced and continuously updated by the appropriate scientific understanding of the analyzed system in real applications.

(1) Climate sustainability can generally be defined by adopting the view that dangerous effects of climate change can be avoided if the increase of global mean temperature does not exceed 2 °C (Schellnhuber et al., 2006; Stern, 2007; IPCC, 2007). This in turn requires that greenhouse gas concentrations are stabilized "at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system" (UNFCCC, 1992). As human-induced climate change is caused by anthropogenic emissions, this level depends on the ability of the environment to absorb these emissions should be regarded as a capacity (C) which allows for a limited amount of total anthropogenic emissions as the utilization of this capacity (with varying annual values of U_r) until 2100 (Allen et al., 2009).

(2) Ensuring sustainability in terms of the proposed concept requires that C and any scenario of $\sum U_r$ are related to each other by estimating the relevant variables while considering data availability and uncertainties, as well as features of the climate system and possible dimensions of policy development (Fig. 1).

Concerning C, the current understanding of the effects of emissions on the climatic system is rather limited. Based on UNEP (2013) and IPCC (2014), it is assumed here for the purposes of the demonstration that this capacity between 2011 and 2100 (i.e., R = 90 years) is about 2150 $GtCO_2$eq. (The cumulative emissions between 2000 and 2011 amounted to about 559 $GtCO_2$eq.) Using such a fixed value assumes that this capacity is mainly non-renewable and cannot be replaced or extended due to natural processes or artificially, but cannot be lost (depleted) due to natural (e.g., due to volcanic eruptions) or human causes, either.

Note that, in lack of the sustainability concept as presented in this paper, the absorption capacity of the air is often reported as annual allowable global emissions, assuming particular annual emission pathways (e.g., Fig. 3.1, page 16 of UNEP, 2013). However, as shown above, and within limits, the annual emission values have nothing to do with sustainability, therefore, scenarios of cumulative emissions over time are used in this demonstration instead where relevant.

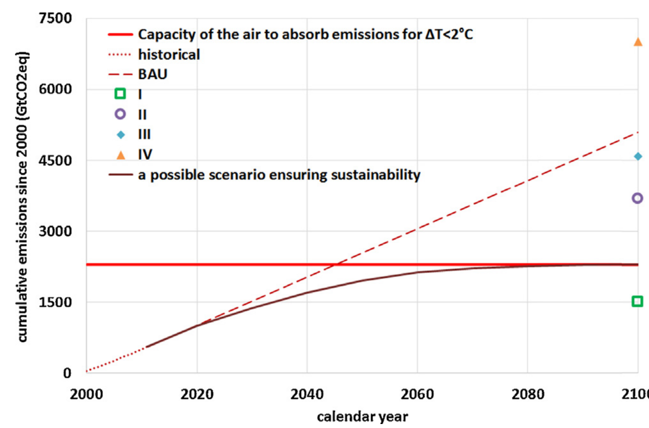

Fig. 1. The capacity of the atmosphere of the Earth (assumed to be non-renewable in the demonstration) to absorb anthropogenic greenhouse gas emissions in 2000 (i.e., C, thick horizontal line) which should not be allowed to be exceeded by cumulative actual annual emissions (i.e., $\sum U_r$) by 2100 to ensure a limited global warming; cumulative global historical emissions 2000–2011 (dashed line); cumulative global emissions by 2100 using a simple linear extrapolation of the recent trend of historical emissions (BAU scenario, dotted line); cumulative IPCC emission scenarios I–IV by 2100 (only represented by their total cumulative emissions in year 2100); and one possible "maximum sustainability pathway" scenario of cumulative emissions by 2100 (thin curve) that aims to keep $\sum U_r$ within C. See text for details.

Depending on assumptions on future economic and social processes, various emission scenarios can be developed between 2011 and 2100 against which C, and thus sustainability can be checked. For the purposes of this demonstration, the current rate of annual emissions is projected to be constant for the BAU scenario. Four other scenarios (IPCC I–IV) are based on the so-called RCP emission scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) of IPCC (2014) with $\sum U_r$ values of 1505, 3690, 4585 and 7005 $GtCO_2$eq, respectively. In these scenarios no pathways of specific annual U_r values are analyzed. Finally, one possible "maximum sustainability pathway" (MSP) scenario is developed so that emissions $\sum U_r$ will deplete C by 2100 when the annual emission, U_{90}, drops to zero (Fig. 1).

(3) Adjusting for uncertainties of estimates, and also for risks that the bona fide implementation of appropriate policies will fail for unknown reasons, is done in this demonstration by adjusting the above mean estimate of the capacity by taking the lower endpoint of its estimated range, 1740 $GtCO_2$eq.

(4) To assess sustainability, all three possible options as described above can be checked.

Option A: In the BAU scenario, the cumulative total emissions will fully deplete the absorbing capacities of the Earth in $R \approx 20$ years, i.e. in a very short period of time. Emission scenarios IPCC II–IV would also lead to unsustainable emissions before 2100 (irrespective of the scenarios of annual emissions), but the time when capacities are depleted depends on the actual emission scenarios (Fig. 1; the actual years are irrelevant here). It is only scenarios IPCC I and the MSP scenarios that ensure sustainability.

Option B: Requiring that $\sum U_r$ do not exceed C until at least 2100 implies (using Eq. (6) as a criterion) that $\sum U_r \leq 1740\,\mathrm{GtCO_2eq}$, which can only be met with the MSP and the IPCC I scenario (MSP is designed to also satisfy Eq. (5), whereas it may need to be checked in the latter case.) (Note that this is equivalent to limiting annual average emissions to around $20\,\mathrm{GtCO_2eq\,yr^{-1}}$, which is much less than global annual emissions in 2010 of about $50\,\mathrm{GtCO_2eq\,yr^{-1}}$).

Option C: Currently estimated capacities are only enough until 2100 in case of scenario IPCC I and the MSP scenario. For all other scenarios, either C should be extended by $\sum U_r - \sum C_r$, if possible, to at least 1950, 2845 and 5265 $\mathrm{GtCO_2eq}$, respectively (using e.g. afforestations or geoengineering), or $\sum U_r$ should be considerably reduced in order to achieve sustainability. One path of such a reduction is the MSP scenario itself.

The above examples also demonstrate the general applicability of the proposed framework in systems where the amount of capacities and utilization rates can be defined and measured using the same units. However, applying the framework may be difficult or impossible in practice due to the lack of the understanding of the system to be analyzed (e.g., due to complexities of ecosystems), data availability, the lack of proper models for projecting future capacity and utilization. Developing appropriate assumptions involved in sustainability assessment may also be difficult as it depends on the characteristics of the environmental system and the assumed needs of human community concerned (at any scale from local to global) and future technological advancement (which might even render the capacity use obsolete or unnecessary). Such assumptions may involve different levels of uncertainty and subjective elements, i.e., human judgment, introducing further complexity in the analysis. Moreover, the quantitative assessment of capacities and/or utility rates may not be possible at an accuracy needed for optimal policy development. The cost of estimating utilization rates and/or capacities, and revising them as appropriate, may also be high. It may also be impossible to judge if an estimated R is high enough or not.

However, the very impossibility of the assessment itself should be taken as important information that there is no firm basis to develop sustainability policy and that further monitoring or scientific and technological developments are necessary to inform policy making. Examples for such a development driven by the need for sustainability policy include the intensification of climate change related research and greenhouse gas emission monitoring systems in the last three decades to meet the information requirements of climate change negotiations and mitigation policies that have aimed at sustaining recent climatic conditions. As a result, we now have much more and much more reliable data to assess the sustainability of the global climate system than before. Efforts to develop ecosystem accounting (Hein et al., 2015) may also offer a way to improve data availability and the basis of sustainability modeling and assessment.

In order that sustainability is achieved, it is also necessary to link the values of U_r, C_r and R to possible policies and actions. Unlike other concepts, the proposed framework is operational in the sense that, provided that all information is available (e.g., Fig. 1), it is not only possible to assess if, and under what conditions, a utilization is sustainable, but also by how much utilization rates should be reduced and/or by how much capacity development is necessary in case an overshoot happens. Such information can be used to develop appropriate sustainability policies and measures, which in turn may require the development of regulation and other social activities. The ways of how the required amount of utilization reductions or capacity enhancements can be achieved, and how policies and measures can be developed, depends on both the physical nature of the specific utilization systems and the specific economic and social circumstances of society.

Finally, as shown above, the lack of a coherent conceptual sustainability framework not only produced many inappropriate indicators, but indicator development might have also sometimes involved political "norm creation" (Rametsteiner et al., 2011), obviously further reducing the effectiveness of indication. The proposed concept of sustainability can help mitigate this situation. For example, just like making sure that a car moves to its destination while always staying within the limits of the road involves the definition of the itinerary and the "road", indicators can be developed to measure how the actual utilization pathways relate to projected ones, and whether any discrepancy is within pre-defined limits. In order to ensure sustainability in already monitored situations, too, existing indicators should also be checked against the above and other ideas based on the proposed concept.

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