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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).