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Towards a comprehensive absolute sustainability assessment method for effective Earth system governance: Defining key environmental indicators using an enhanced-DPSIR framework

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ABSTRACT

Reflecting the growing interest in the concept of absolute sustainability, this research defines an absolute sustainability assessment method (ASAM) with three key characteristics: (i) assessment of a comprehensive range of environmental impacts in absolute terms; (ii) evaluation of these impacts at an early stage in impact pathways; and (iii) the capacity to assess these impacts at multiple economic levels. To that end, using an enhanced Driver-Pressure-State-Impact-Response (eDPSIR) framework, this study systematically classified the environmental indicators reported in the Planetary Boundaries (PBs), Life Cycle Assessment (LCA) and Sustainable Development Goals (SDGs) by mapping them on to a network of cause-effect chains developed in previous work, and extended to include the areas of protection in LCA. It was found that twelve major environmental problems could be defined as key central nodes in this causal network, and that the PBs and LCA evaluated many of these environmental problems at an early stage in the causal network while the SDGs generally addressed similar problems at the latter end of the causal network. Six of these environmental problems were addressed in all three approaches (PBs, LCA and SDGs) and the others were addressed in one or two approaches. An associated (but incomplete) set of absolute environmental sustainability indicators were identified that are already available in one or more of the three approaches; some of these indicators require further methodological development in order to support the advancement of an ASAM for effective Earth system governance.

1. Introduction

The concept of *sustainable development* has emerged out of a growing awareness of the global interrelationships between environmental impacts and the socio-economic dimensions of human activities (Hopwood et al., 2005). However, a fundamental debate regarding sustainable development is whether we should subscribe to a strong or a weak conception of sustainability. A weak conception of sustainability assumes that natural capital (e.g. mineral resources, clean air, fertile soil) and manufactured capital (aka physical capital, e.g. machines, buildings) are substitutable (Brekke, 1997; Daly et al., 1994; Pezzey, 1992; Pezzey et al., 1990). According to this perspective, the aggregated stock of both types of capital should be increased or at least maintained for future generations, and there is a general expectation that technical solutions can compensate the environmental impacts that are (usually) associated with the supply of manufactured capital (e.g. construction of a water treatment plant in place of a wetland to deliver the service of water filtration) (Pezzey, 1992; Pezzey et al., 1990). Effectively this means that, from a weak sustainability perspective, achieving economic growth to supply manufactured capital at the cost of environmental degradation is acceptable (Daly et al., 1994; Jacobs and Stott, 1992).

In contrast, a strong conception of sustainability suggests that the different types of capital are not substitutable i.e. economic growth should not be achieved at the cost of environmental degradation (Daly et al., 1994; Jacobs, 1991; Jacobs and Stott, 1992). The concept of *critical* natural capital is therefore fundamental in strong sustainability i.e. natural capital that is essential to the continued efficient functioning of the Earth system and human well-being. Examples of critical natural capital include the ozone layer and the global atmosphere whose functions cannot be substituted by other types of capital (Chiesura and de Groot, 2003; Ekins et al., 2003). In contrast, manufactured capital is reproducible (Ekins et al., 2003; Turner, 1993); for instance, built infrastructure can be reconstructed if it is destroyed but loss of species is

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irreversible. Moreover, in many cases, production of manufactured capital relies heavily on natural capital (Ekins et al., 2003); for example, building construction requires raw materials extracted from the Earth or harvested from ecosystems (e.g. mineral ores such as iron and aluminium, and wood). Furthermore, we have a limited understanding of the functioning of natural systems, and destruction of natural capital may have impacts on human well-being beyond those we can currently predict (Ekins et al., 2003; Patrício et al., 2016; Rockström et al., 2009).

In reality, a weak sustainability perspective has been adopted by governments in many countries as they focus on realising socio-economic benefits and minimise or ignore the associated environmental degradation (Kim and Bosselmann, 2015; Muys, 2013). As a result, many of the Earth system boundaries are already transgressed (ranging from global warming to air pollution, water quality degradation and loss of ecosystems). This has been highlighted in the last few years through the concept of Planetary Boundaries proposed by Rockström et al. (2009) and elaborated by Steffen et al. (2015). It means, that today, human societies need to urgently address two interrelated "wicked" problems on a global scale: (i) how to protect the entire Earth system and its subsystems (in particular, the stock of critical natural capital), and (ii) how to operate socio-economic systems within the Earth system boundaries. This, therefore, implies the adoption of a strong sustainability conception in order to achieve sustainable development.

In the context of addressing these two wicked problems, this article introduces a proposal for developing an absolute sustainability assessment method (ASAM) for effective Earth system governance. The term "Earth system governance" refers to the process of defining and developing socio-economic systems that will prevent drastic Earth system disruptions (Biermann et al., 2010, 2012). Section 2 provides an overview of existing environmental sustainability assessment methods and discusses their potential to address absolute sustainability. Section 3 introduces the proposed ASAM and describes the systematic classification process for existing environmental indicators, and Section 4 presents the key findings of the classification. Section 5 concludes the article with a discussion on the contribution of this work in developing the proposed ASAM, and reports the limitations of the study that require further exploration.

2. Current state of research on environmental sustainability assessment methods addressing absolute sustainability

2.1. Role of environmental sustainability assessment methods in Earth system governance

As outlined above, there are a number of complexities inherent in effective Earth system governance. Robust and comprehensive environmental sustainability assessment methods (ESAMs) are required to address these complexities for any given system under analysis and proposed interventions (e.g. Moldan et al., 2012; Ness et al., 2007; Singh et al., 2009). A comprehensive ESAM should address the following questions: (Q1) What is the environmental impact(s) of a chosen system? (Q2) What is the allocated biophysical limit(s) of the Earth system (aka the desired state) for the chosen system? and (Q3) How can proposed interventions in the system be measured with respect to their ability to bring the system within these biophysical limits? Here, the term "system" could be either a product, process, project, sector, nation or the entire Earth (Roos et al., 2016).

With regard to Q1, there exist a large number of ESAMs such as Environmental Impact Assessment, Life Cycle Assessment (LCA) and environmental footprints that quantify the environmental impact(s) of a system (Moldan et al., 2012; Ness et al., 2007; Singh et al., 2009). These ESAMs, in general, either implicitly or explicitly rank a particular system in relation to a reference system that is relevant to the nature (or the function) of the examined system and the objectives of the study. For example, they address issues such as "Is System A better than System B?" and "Which activity in the examined system is responsible for the most of the environmental impacts?" As a result, such ESAMs generally do not provide information on the environmental sustainability performance of the system with regard to the allocated biophysical limits of the Earth system, and are therefore classified as relative sustainability assessment methods using relative environmental sustainability indicators (Bjorn et al., 2016; Hauschild, 2015).

On the contrary, ESAMs addressing Q2 and Q3 require the development of absolute environmental sustainability indicators (AESIs). AESIs are indicators that benchmark the actual environmental impact (s) of a system against a set of environmental targets or standards (Bjørn et al., 2016). These targets can be either policy targets or biophysical (science-based) thresholds. However, only a few such ESAMs (with AESIs) have been developed, for example, Tolerable Windows (Bruckner et al., 1999), Planetary Guardrails (German Advisory Council on Global Change, 2011) and Planetary Boundaries (Rockström et al., 2009; Steffen et al., 2015). Tolerable Windows benchmarks climate change impacts against a set of pre-defined targets (Bruckner et al., 1999), whilst Planetary Guardrails does it for a list of environmental problems including climate change, soil degradation, biodiversity loss, and ocean acidification (German Advisory Council on Global Change, 2011). Similarly, the concept of Planetary Boundaries (PBs) presents a set of control variables and thresholds for nine critical Earth system processes (see Rockström et al., 2009; Steffen et al., 2015).

2.2. Adaptation of existing environmental sustainability assessment methods to develop absolute environmental sustainability indicators

Recognising that only a few ESAMs address Q2 and Q3, and that there is potential for modifying LCA indicators into AESIs, some LCA researchers have used distance-to-target (DTT) methods at the Life Cycle Impact Assessment phase of an LCA (e.g. Bjørn and Hauschild, 2015; Castellani et al., 2016; Seppälä and Hämäläinen, 2001; Wang et al., 2011). These DTT methods derive weighting factors for LCA impact categories by comparing a system's actual environmental performance against existing environmental targets (Castellani et al., 2016). However, many of the studies published to date have adopted policy-based targets and benchmarked the sustainability performance of a particular system mostly at a regional or national level (e.g. Castellani et al. (2016) for Europe; Wang et al. (2011) for China; and Frischknecht and Büsser Knöpfel (2013) for Switzerland). The policy-based targets generally represent a compromise between scientific knowledge and societal considerations (political feasibility, cost), and hence they are (usually) less strict than science-based targets (Acosta-Alba and Van der Werf, 2011). Acknowledging that, Bjørn and Hauschild (2015) explored how science-based targets (i.e. PBs in this context) can be adopted in the DTT methods to address absolute environmental sustainability at the global as well as regional (for Europe) levels. Following this study, other studies exploring the potential to use the PBs in combination with LCA indicators to benchmark the environmental sustainability performance of systems at different economic levels are emerging (e.g. Fang et al., 2015; Nykvist et al., 2013; Roos et al., 2016; Sandin et al., 2015). For instance, Roos et al. (2016) and Sandin et al. (2015) benchmarked the sustainability performance of the Swedish apparel sector in terms of climate change, freshwater consumption and non-renewable energy resources, and calculated impact reduction targets at both sectoral and product levels. Similarly, Fang et al. (2015), at the national level, benchmarked the sustainability performance of 28 countries with regard to the climate change, land-use and freshwater use PBs.

Although such PBs-based LCA studies have begun to inform environmental sustainability performance of systems at different economic levels and in absolute terms, there are a number of outstanding challenges in undertaking these types of studies. These include: identifying and addressing the overlaps between the Earth system processes identified in the PBs; including spatial differentiation of control