Exploring the Linkages Between the Environmental Sustainable Development Goals and Planetary Boundaries Using the DPSIR Impact Pathway Framework

Chanjief Chandrakumar and Sarah J. McLaren

Abstract Most of the conventional environmental sustainability assessment methods, such as Life Cycle Assessment and environmental footprints, evaluate economic goods and services in terms of the nature or the function of the studied systems. As such, these methods overlook the variations in the overall magnitude of production and consumption patterns for the examined systems. As a result, the progress achieved in mitigating global environmental problems is likely to be slow and may be insignificant. Hence this study explores the interlinkages between the Sustainable Development Goals (SDGs) and Planetary Boundaries (PBs) using an DPSIR (Drivers-Pressures-State of the Environment-Impacts-Responses) impact pathway framework—in support of developing an absolute sustainability assessment method (ASAM). The study demonstrates that there is a substantial overlap between the SDGs and PBs. The science-based thresholds listed in the PBs can therefore be adopted as a complementary set of environmental boundaries for the SDG indicators. Overall, the study lays the foundation for advancing an ASAM that can guide policy- and decision-makers to operationalize the SDGs effectively.

1 Introduction

The Planetary Boundaries (PBs) concept was introduced by Rockström and his associates [1], and was updated by Steffen et al. [2]. Rockström et al. proposed nine critical Earth system processes and associated control variables and thresholds, claiming that transgressing any of the thresholds would potentially be devastating

C. Chandrakumar (✉)

New Zealand Life Cycle Management Centre, School of Agriculture and Environment, Massey University, Palmerston North 4442, New Zealand
e-mail: C.Chandrakumar@massey.ac.nz

S. J. McLaren

School of Engineering and Advanced Technology, Massey University, Palmerston North 4442, New Zealand

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E. Benetto et al. (eds.), *Designing Sustainable Technologies, Products and Policies*, https://doi.org/10.1007/978-3-319-66981-6_46

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for human societies [1]. Based on the nine PBs, a safe operating space for humanity was determined [1, 2]. Here, the safe operating space refers to a relatively stable state called the *Holocene* epoch, in which human societies can continue to develop and thrive [2]. Today, both the scientific and political communities have agreed upon the notion that there are global limits for the Earth system and they should be respected. Consequently, studies adopting the PBs have started proliferating, and they can be classified into works that (i) define or refine the control variables and the associated thresholds [e.g. 1, 2], (ii) downscale the global PBs to sub-global levels [e.g. 3, 4], (iii) set impact reduction targets [e.g. 3, 4], and (iv) devise policies and strategies [e.g. 3, 5].

While the PBs concept sets global limits for environmental impacts to benchmark a system's performance globally, environmental sustainability assessment methods (ESAMs) such as Life Cycle Assessment (LCA) and environmental footprints evaluate the environmental performance of a so-called product system (which is usually defined in terms of supplying a specified quantity of an economic product or service). Generally, the outcomes of an LCA or environmental footprint study guide decision makers to improve the eco-efficiency of the chosen product system through identifying the environmental hotspots along its life cycle [6]. As a result, use of LCA and other related life cycle thinking approaches to support decision-making has become common within the business and academic communities [6]. However, although the outcomes of these studies guide eco-efficiency improvements, the overall progress achieved in mitigating environmental problems still remains slow and insignificant [7–9]. One contributing factor is that conventional ESAMs like LCA do not benchmark the environmental sustainability performance of a system against a set of environmental boundaries (or standards). Instead, they rank a particular system in relative terms, by comparing it with a reference system that is relevant to the nature or the function of the system under investigation, and thus, the variations in the consumption and production patterns of the examined products and services are overlooked [7–9]. For example, Product A may be superior (or more sustainable) than Product B in terms of eco-efficiency, but neither could be sustainable on an absolute scale due to the predicted growth in global production and consumption volumes of the product [7, p. 325].

Therefore, recently, the scientific community began to focus on the so-called concept of *absolute sustainability*. Absolute sustainability is focused on how human societies can operate within the *carrying capacity* of the Earth system [8, 9]. Here, the term “carrying capacity” refers to “the maximum sustained environmental interference a particular system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert” [6, p. 1007]. As a result of growing interest in absolute sustainability, scientists have started developing absolute sustainability assessment methods (ASAMs) by supplementing the existing ESAMs with the Earth's carrying capacity [6, 8, 9], for instance, supplementing the ecological footprint with the Earth's biocapacity (available bio-productive area) [e.g. 10], LCA with PBs [e.g. 6, 8] and environmental footprints with PBs [e.g. 5].

2 Operationalisation of Sustainable Development Goals

The United Nations agreed on a set of Sustainable Development Goals (SDGs) in 2015 comprising 17 goals, 169 targets and 232 indicators [11, 12]. The SDGs aim to cover a wide range of sustainable development problems [12–14]. Overall, the SDGs are intended to be universal with a shared common vision of progressing towards a safe, just and sustainable operating space for human societies [12, 16]. However, the SDGs have been criticised as being difficult to implement due to having too many goals and targets, lacking clarity, and having overlapping objectives [16]. Additionally, the SDG proposed for safeguarding the Earth system have been criticised as being neither sufficiently comprehensive nor ambitious [13, 14]. For instance, many of the SDG indicators have been proposed without a relevant environmental boundary. Researchers therefore have begun exploring how to operationalize the SDGs within the Earth's carrying capacity, and specifically how to link them to the PBs and then to LCA [13, 15]. Dong and Hauschild classified the indicators proposed in the SDGs, PBs and LCA using an DPSIR (Drivers-Pressures-State of the Environment-Impacts-Responses) impact pathway framework (see [20] for DPSIR impact pathway framework) and showed that all three approaches overlap in terms of seven impact categories (climate change, acidification, ozone depletion, eutrophication, chemical pollution, freshwater use and change in biosphere integrity) [15]. However, the study used the older version of the SDGs listed in [11] and until recently, no studies have explored the interlinkages between the latest SDGs listed in [12], the PBs and LCA. Additionally, the potential for operationalizing the SDGs using an ASAM had not been explored yet. Therefore, this study identifies the SDG indicators that evaluate environmental problems, and then systematically explores the interlinkages with the PBs.

To that end, the rest of the paper is organised as follows: Sect. 3 outlines the ASAM framework presented in [17]. Sect. 4 establishes the interlinkages between the environmental SDGs and PBs, and Sect. 5 summarises how this work underpins the development of the proposed ASAM.

3 Outline of the Proposed Approach

The aim of the proposed ASAM is to operationalize the SDGs at sub-global levels (e.g. country, region, organisation, product) by estimating environmental boundaries at these different levels [17]. These boundaries can then be used to calculate distance-to-target measurements through benchmarking the system's (e.g. country, region, organisation, product) performance against the estimated boundaries. This involves, firstly, identifying the SDG indicators concerned with the conventional areas of protection (AoPs) used in LCA i.e. *human health*, *ecosystem quality*, *resource scarcity* and *man-made environment* [18].

According to [6, 19], many of the PB control variables differ from the indicators of the conventional ESAMs (including LCA), particularly with respect to the point of impact assessment although these indicators evaluate similar kinds of environmental impacts to those reported in the PBs. Hence, the chosen SDG indicators and the PB control variables are further classified into driver, pressure, state, impact and response indicators using an DPSIR impact pathway framework. Having classified them, the interlinkages between the SDGs and PBs are explored. This enables subsequent development of a complementary set of global boundaries for the SDG indicators using, where appropriate, the thresholds proposed for the control variables in the PBs. Afterwards, the global boundaries can be allocated to lower economic levels using a top-down approach. The method is operationalised by developing distance-to-target measurements based on the calculated environmental boundaries compared with the current environmental performance of the systems under analysis (calculated using conventional ESAMs like LCA and environmental footprint studies). These distance-to-target measurements could be positive or negative depending on whether the system is performing in line with the goals and targets reported under the SDGs.

4 Linkages Between the SDGs and PBs

This section details how the PBs can be employed as a complementary set of global boundaries for the SDGs by providing a systematic comparison between the SDG indicators and the PB control variables. Firstly, the SDG indicators concerned with the AoPs of *human health*, *ecosystem quality*, *resource scarcity* and *man-made environment* were chosen (a total of 73 indicators). This set of SDG indicators comprised all the SDG indicators under the SDGs for clean water and sanitation (SDG 6), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (SDG 14) and life on land (SDG 15), plus CO₂ emission per unit of value added (SDG Indicator 9.4.1), economic loss due to natural disasters (SDG Indicator 1.5.2), levels of fine particulate matter in cities (SDG Indicator 11.6.2), and proportion of land for sustainable agriculture (SDG Indicator 2.4.1). Then, as outlined in Sect. 3, the chosen SDG indicators were mapped onto a network of cause-effect chains (developed based on the environmental problems addressed in the SDGs and PBs) along with the PB control variables and linked together wherever relevant (see Fig. 1). This mapping step further classified the SDG indicators into driver (0 SDG indicators), pressure (2 SDG indicators), state (19 SDG indicators), impact (14 SDG indicators) and response (38 SDG indicators) indicator categories.

As emphasised in [1, 2], human societies should be operating within the thresholds reported in the PBs. Therefore, this section focuses on the PBs and discusses how each PB (shown in bold text) is related to different SDGs. Steffen et al. introduced a PB called “**freshwater use**” and two control variables to evaluate the challenges resulting from absolute water withdrawals [2]. The proposed control

Fig. 1 The identified interlinkages between the SDGs and PBs

variables estimate the associated impacts at the global as well as the basin levels [2], and inform the impacts at the pressure point of the DPSIR impact pathway (see Fig. 1). Likewise, SDG Indicator 6.4.1 evaluates the same problem at the pressure point in the impact pathway (in terms of water use efficiency). Consequently, at the state point, SDG Indicator 6.4.2 accounts for the effects of excessive water withdrawals (i.e. the level of water stress), which is similar to the PB control variable [12]. However, the proposed SDG indicators do not include any absolute limits. We, therefore, recommend deploying the thresholds proposed for the freshwater use PB because the control variables and the SDG indicators largely overlap; and both inform the impacts at the pressure or state point in the impact pathway.

Increasing atmospheric CO₂ concentration and the associated CO₂ uptake by the oceans have resulted in ocean acidification problems [2]. As a consequence, a PB called “**ocean acidification**” was introduced with a control variable (state point) and a threshold for carbonate ion concentration in terms of aragonite [2]. Meanwhile, the SDGs advanced an indicator (SDG Indicator 14.3.1) that estimates the pH level of the oceans [12]. Although the control variable and the SDG Indicator apply different units to track the ocean acidification effects, the objective and the point of assessment in the DPSIR framework are the same. Moreover, both the SDG indicator and the control variable evaluate the impacts on an absolute scale. We, therefore, comprehend that the ocean acidification impacts can be measured in terms of either aragonite or pH level of the oceans.

The “**changes in biosphere integrity**” PB adopts two control variables to assess the two components of the biosphere: genetic and functional diversity [1, 2]. The first component evaluates the extinction of species due to human pressures, whereas the second estimates the loss of biodiversity at different ecosystem levels. According to Fig. 1, the impacts pertaining to the both components are expressed at the impact point of the DPSIR impact pathway. In this regard, the SDGs also propose a set of indicators for protecting terrestrial, marine and freshwater ecosystems [12]. SDG Indicators 14.4.1 and 14.5.1 estimate the proportion of fish stocks existing within the biologically sustainable levels and the coverage of protected marine areas, respectively. Moreover, SDG Indicator 6.6.1 tracks the changes occurring in both marine and freshwater ecosystems due to water quality degradation. Although these SDG indicators implicitly underpin the significance of operating within the Earth’s carrying capacity, no relevant boundaries have been reported. However, given that the objectives of these control variables overlap with the SDG indicators, it makes sense to supplement the SDG indicators with the thresholds proposed for the “changes in biosphere integrity” PB to inform the environmental impacts in terms of genetic and functional diversities on an absolute scale.

Considering the intensive use of nutrients and the associated eutrophication effects in major ecosystems, Steffen et al. proposed the so-called “**biogeochemical flows**” PB and two associated control variables [2]. These control variables evaluate the eutrophication effects in oceanic, freshwater and terrestrial ecosystems. Given that the major eutrophication problems arise from N and P fertiliser use and the control variables evaluate the impacts at the pressure point (as shown in Fig. 1),

thresholds have been set for N and P fertiliser application [2]. Likewise, SDG Indicator 14.1.1 evaluates the problem of marine eutrophication resulting from land-based activities, including nutrient pollution [12]. Since both SDG Indicator 14.1.1 and the relevant control variables refer to the same problem of eutrophication, and particularly at the same point of the impact pathway (i.e. pressure), the PB thresholds can be used as they are complementary to SDG Indicator 14.1.1.

Changes in land use have significant effects on several biological and ecological systems, including climate and water. For example, changes in the area of boreal forests particularly affect the albedo of the land surface, and changes in the area of tropical forests specifically affect global evapotranspiration rates [2]. For this purpose, a PB called “**land-system change**” is suggested, which estimates the loss of forest cover at the state point of the impact pathway (see Fig. 1). Similarly, the SDGs report a set of indicators that evaluate the environmental problems resulting from forest cover loss as well as loss of other biomes [12]. For instance, SDG Indicator 15.1.1 estimates the ratio between forest and total land area, SDG Indicator 15.1.2 measures the proportion of protected areas for terrestrial, freshwater and mountain biodiversity, and, SDG Indicator 15.4.1 estimates the land coverage allocated for mountain biodiversity. Nonetheless, none of these SDG indicators assesses the environmental degradation on an absolute scale. Rather, they merely report the proportions of the protected and degraded lands.

We, hence, recommend using SDG Indicator 15.1.1 along with the threshold proposed for the land-system change PB for estimating the loss of forest cover on an absolute scale. However, since the PB focuses solely on the loss of forest cover, there remains a research gap in identifying relevant thresholds for other biomes addressed in SDG Indicators 15.1.2 and 15.4.1.

The “**climate change**” PB and its associated control variables emphasise that the atmospheric CO₂ concentration and the radiative forcing from greenhouse gases (GHGs) should be reduced to 350 ppm CO₂ (350–450 ppm) and to 1 Wm⁻² respectively (at the state point in the DPSIR impact pathway) [2]. But limiting the atmospheric concentration to 350 ppm CO₂ is unlikely as the current values of the control variables are 399 ppm CO₂ and 2.3 Wm⁻² [2], and the world population and economy are still growing [21]. The IPCC therefore suggests that achieving a concentration of 450 ppm CO₂ is more likely [21, p. 12]. On the other hand, the SDGs present a set of SDG indicators concerned with mitigation of climate change problems [12]. At the response point, SDG Indicator 13.1.1 estimates the fatalities and injuries due to climate change impacts, whereas SDG Indicators 13.1.2, 13.1.3 and 13.2.1 focus on adopting policies and strategies to avert climate change impacts. SDG Indicators 13.3.1, 13.3.2, 13.a.1 and 13.b.1 aim to strengthening institutional, systemic and individual capacity-building to implement adaptation, mitigation and technology transfer and development actions. In addition, SDG Indicator 9.4.1 quantifies the carbon intensity of industries at the pressure point. In general, except SDG Indicator 9.4.1, others focus only on averting the climate change impacts (as seen in Fig. 1), and none of them evaluates the climate change impacts on an absolute scale. Therefore, to our understanding, the PB thresholds

(and the corresponding global carbon budget) can be used as a set of global boundaries for SDG Indicator 9.4.1.

The “**atmospheric aerosol loading**” PB evaluates the impact resulting from the emissions of black and organic carbon from sources like cooking and heating with biofuels and diesel transportation, whereas the “**introduction of novel entities**” PB refers to the persistence, mobility and impacts of chemicals and other types of engineered materials or organisms produced by human activities [2]. Similarly, the “**stratospheric ozone depletion**” PB concentrates on the ozone concentration variations resulting due to synthetic chemicals release [2]. Interestingly, the associated control variables of these three PBs express the impacts at the state point of the DPSIR impact pathway. As far as we understand, some of the SDG indicators evaluate similar environmental impacts, but not explicitly. SDG Indicator 11.6.2 monitors the levels of fine particulate matter in cities at the state point (with a focus on human health), whereas SDG Indicators 11.6.1 and 12.4.2 quantify the solid and hazardous waste generated (pressure point). SDG Indicator 12.4.2 also quantifies the amount of hazardous waste treated (response point) and SDG Indicators 12.4.1 and 12.7.1 focus on the global initiatives taken to develop multinational agreements and policies on hazardous waste and other chemicals (response point). Although there are some overlaps between the above-listed three PBs and the SDG indicators, it would not be advisable to use them in a complementary way for the following reasons: (i) existence of an enormous number of hazardous substances (including chemicals); (ii) no SDG indicators directly assess the effects of ozone depletion; (iii) no control variables and thresholds have been proposed for the “introduction of novel entities” PB; (iv) the effects of some substances are still unknown, and some effects are not readily reversible; and (v) the PBs are located closer to the original activities that cause the environmental impacts, whereas the SDGs focus on waste management, and are generally located at the response point [2]. Further research is therefore needed to understand better the complementarities between these PBs and the SDGs.

In sum, the environmental SDG indicators mostly address the environmental problems reported in the PBs, which are primarily associated with the *ecosystem quality* AoP. However, in contrast to the PBs, the SDGs additionally concentrate on the AoPs *human health*, *resource scarcity* and *man-made environment* through addressing the global challenges of unsustainable food and agriculture, soil quality degradation, impacts of ecosystem degradation on human health, direct human impacts on ecosystem (wildlife trafficking and poaching, and overfishing) and lack of infrastructure for water quality and resources management by communities [12]. Regarding unsustainable food and agriculture, SDG Indicator 2.5.1 estimates the number of plant and genetic resources secured for sustainable food and agriculture, whereas SDG Indicator 2.5.2 estimates the local breeds under risk of extinction. Likewise, SDG Indicator 2.4.1 evaluates the soil quality degradation. Nevertheless, these SDG indicators are suboptimal because they use a relative scale, and lack clarity; for instance, SDG Target 2.4 (which includes SDG Indicator 2.4.1) focuses on multiple environmental problems, including climate change and soil quality degradation [12, 14].

On the other hand, a set of SDG indicators has been reported to evaluate the impacts of degradation of ecosystems on human health. SDG Indicators 3.9.1, 3.9.2, 6.3.1 and 6.3.2 evaluate the human health problems resulting due to ambient air pollution, unsafe water, sanitation and hygiene, whereas SDG Indicator 3.9.3 assesses the health problems resulting from unintentional poisoning [12]. Additionally, SDG Indicators 2.4.1, 2.5.1 and 2.5.2 explicitly refer to the impacts on human health as a consequence of unsustainable food production and agricultural practices. Likewise, SDG Indicators 15.7.1 and 15.c.1 estimate the impacts of wildlife trafficking and poaching, whereas SDG Indicators 14.4.1 and 14.5.1 addresses the impacts associated with overfishing. Regarding lack of infrastructure for water quality and resources management by communities, SDG Indicators 6.1.1, 6.2.1 and 6.a.1 concentrate on developing infrastructure for effective water resources management [e.g. 12, 16].

5 Conclusions

The study underpins the development of an ASAM framework by systematically exploring the interlinkages between the SDGs and PBs using an DPSIR impact pathway framework. With to the analysis presented in Sect. 4, the two approaches demonstrate notable overlaps with regard to their indicators and control variables. Each of the PBs is linked to one (or more) SDG indicator(s), as shown in Fig. 1. In particular, the **“freshwater use”**, **“ocean acidification”**, **“biogeochemical flows”**, **“land system change”** and **“change in biosphere integrity”** PBs exhibit sound linkages with the SDG indicators. Interestingly, some of the control variables of these five PBs are located at the same point of the DPSIR impact pathway as the SDG indicators. But, in contrast, the **“climate change”** PB control variable is located at the state point of the impact pathway, whereas the SDG indicators associated with climate change are mostly located at the response point, except SDG Indicator 9.4.1, which estimates the carbon intensity of industries at the pressure point. Moreover, no SDG indicators report an absolute limit for GHG emissions. The **“introduction of novel entities”** and **“atmospheric aerosol loading”** PBs show some overlaps with SDG Indicators 11.6.1, 11.6.2 and 12.4.2, whereas no explicit linkages are found between the **“stratospheric ozone depletion”** PB and the SDG Indicators. Furthermore, as discussed in Sect. 4, the SDGs additionally shed light on some other global challenges not explicitly addressed in the PBs such as unsustainable food and agriculture, soil quality degradation, impacts of ecosystem degradation on human health, direct human impacts on ecosystem (wildlife trafficking and poaching, and overfishing), and lack of infrastructure for water quality and resources management by communities.

Overall, according to this study, it seems potentially feasible to adopt the science-based thresholds reported in the PBs as a complementary set of global boundaries for the SDG indicators. Moreover, advancing appropriate environmental boundaries for the additional challenges addressed in the SDGs, and using them

alongside the PB thresholds, will provide a platform to benchmark the environmental sustainability performance of a system at a global level. However, further research is necessary to benchmark similar environmental impacts on a sub-global level, given that most of the impacts are, in fact, a result of the accumulated effects of discrete regional and local problems [2, 4]. Hence, some suggest allocating the global boundaries to sub-global levels using a variety of allocation principles [e.g. 3, 4], while others propose developing appropriate independent boundaries at sub-global levels [e.g. 2, 6, 8].

Finally, in order to develop an ASAM framework, future studies should focus on linking the SDGs and PBs with the Impact Assessment phase of LCA. Such an ASAM has potential to inform whether the chosen system is aligned (or not) with the environmental goals and targets listed in the SDGs as well as whether they are operating within the carrying capacity of the Earth system.

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