Ecological Indicators 69 (2016) 836–849

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Tracking resource use relative to planetary boundaries in a steady-state framework: A case study of Canada and Spain

Andrew L. Fanning[a,b,*], Daniel W. O'Neill[b,c]

[a] Faculty of Marine and Environmental Sciences, University of Cádiz, Polígono Río San Pedro s/n, Puerto Real, 11510, Cádiz, Spain
[b] Center for the Advancement of the Steady State Economy, 5101 S. 11th St., Arlington, VA, 22204, USA
[c] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form 22 March 2016
Accepted 19 April 2016

Keywords:
Planetary boundaries
Environmental footprints
Steady-state economy
Indicators
Input-output analysis

ABSTRACT

There is a growing understanding of the biophysical processes that regulate the stability of the Earth-system, yet human pressures on the planet continue to increase rapidly. Here, recent advances in defining Earth-system thresholds using the planetary boundaries framework are translated down to national and sub-national levels. A set of 10 indicators is developed in a biophysical accounting framework that links the sustainability of resource flows from the biosphere to final consumption. The indicator set includes three measures of physical stocks, three measures of aggregate resource consumption, and four indicators of sustainable scale. The four scale indicators are ratios of (i) cumulative carbon footprint relative to carbon budget, (ii) nutrient use relative to biogeochemical boundaries, (iii) blue water consumption relative to monthly basin-level availability, and (iv) land footprint relative to biocapacity. Taken together, the indicators measure how close high-consuming societies are to meeting the conditions of a "steady-state economy", defined here as an economy with non-growing physical stocks and flows maintained within shares of planetary boundaries. The framework is applied over a 15-year period to the economies of Canada and Spain, along with two sub-national regions (Nova Scotia and Andalusia). Nova Scotia is the only study site experiencing stable or decreasing biophysical stocks and flows. None of the study sites are consuming resources within their shares of all four planetary boundaries. Overall, the set of indicators provides guidance for prioritizing which environmental pressures need to decline (and by how much) for societies to be more effective stewards of Earth-system stability.

1. Introduction

There is convincing evidence that humanity's central role in geology and ecology has ushered in a new epoch, the Anthropocene, whereby our activities are already pushing the Earth-system rapidly into a "less biologically diverse, less forested, much warmer, and probably wetter and stormier state" (Steffen et al., 2007: 614). Rockström et al. (2009) define planetary boundaries for nine Earth-system processes whose transgression risks altering the planet's remarkably stable Holocene-like state of the past ~10,000 years. Maintaining the Earth-system in Holocene-like conditions is desirable because these are the only conditions that are known with certainty to be capable of supporting modern society.

The planetary boundaries framework has been the subject of considerable attention and debate from both scientific and policy perspectives. From a scientific viewpoint, Steffen et al. (2015) provide a revised update to the boundaries framework that incorporates specific inputs from researchers along with more general advances in Earth-system science over the past six years. From a policy point of view, one of the main obstacles impeding the application of the planetary boundaries framework in national and/or regional development planning is that the boundaries were not designed to be "disaggregated" to smaller levels (Steffen et al., 2015). However, there is a need to translate the alarming evidence from Earth-system science to national and sub-national levels where the governance of natural resources predominantly takes place.

To date, there are only a few studies that utilize "planetary boundary thinking" to define ecological boundaries at lower levels. The planetary boundaries framework (i) identifies key processes that regulate Earth-system stability, (ii) chooses appropriate control variables to measure these processes, (iii) attempts to define

* Corresponding author at: Faculty of Marine and Environmental Sciences, University of Cádiz, Polígono Río San Pedro s/n, Puerto Real, 11510, Cádiz, Spain.
E-mail address: afanning42@gmail.com (A.L. Fanning).

http://dx.doi.org/10.1016/j.ecolind.2016.04.034
1470-160X/

the range of uncertainty within which a threshold effect could occur, and finally (iv) proposes a boundary on the lower bound of uncertainty based on the precautionary principle (Rockström et al., 2009).

A bottom-up approach to defining national or sub-national ecological boundaries maintains the four-step logic of the original planetary boundaries framework but adapts the first and/or second steps to fit the scope of the analysis in question. Dearing et al. (2014) case study of two Chinese localities is a bottom-up analysis that defines ecological processes and control variables based wholly on local environmental conditions within the case study sites. A top-down approach, on the other hand, adheres strictly to the Earth-system processes and control variables defined at the planetary level, while attempting to disaggregate them to lower levels. Nykvist et al. (2013) use a top-down approach to attribute and compare national shares of four disaggregated planetary boundaries (climate change, freshwater use, land-system change, and nitrogen) across 61 countries. In a South African case study, Cole et al. (2014) apply an interesting mix of both top-down and bottom-up approaches, depending on whether the specific environmental dimension is characterized as a global boundary, a national limit or a local threshold.

The present article contributes to the nascent literature seeking to define maximum sustainable thresholds for national and sub-national resource use based on shares of global Earth-system boundaries. Like Nykvist et al. (2013), we adopt a top-down approach in order to compare the national and sub-national biophysical performance of high-consuming societies relative to their respective shares of planetary boundaries. We track four indicators of environmental pressure relative to disaggregated planetary boundaries: (i) cumulative carbon footprints relative to carbon budgets, (ii) nutrient use (nitrogen and phosphorus) relative to biogeochemical boundaries, (iii) blue water consumption relative to monthly basin-level availability, and (iv) land footprints relative to biocapacity.

Additionally, the analysis presented here embeds the planetary boundaries framework for the first time within the concept of a steady-state economy. Daly (2008) defines a steady-state economy as "an economy with constant population and constant stock of capital, maintained by a low rate of throughput that is within the regenerative and assimilative capacities of the ecosystem" (Daly (2008):3). It is important to note that advocates of a steady-state economy make no call for holding steady those non-physical aspects of individual and collective betterment that can be achieved without growing the physical size of the economy on our finite planet. Here, we define a steady-state economy as *an economy with constant population and constant stock of physical capital, maintained by a low rate of throughput that is within safe boundaries of intrinsic biophysical processes that regulate the stability of the Earth-system*.

The main objective of our analysis is to develop and apply an integrated biophysical accounting framework that incorporates the safe operating space of the planetary boundaries framework explicitly into the measurement of steady-state economies. The idea that voluntarily transitioning from a growth-based economy to a steady-state would be a desirable goal for society dates back to the classical economist Mill (1848). That being said, O'Neill (2015a) provides the only analysis to our knowledge that estimates national economy-wide trends in physical stocks and material/energy flows with the intent of explicitly measuring their proximity to the steady-state conditions of sustainable scale and biophysical stability.

A set of 10 indicators is developed here in a biophysical accounting framework that links resource flows from the biosphere to the scale of the production of goods and services for final consumption. Accompanying the four indicators of sustainable scale described above, the indicator set also includes three measures of change in physical stocks (population, livestock and built capital) and three measures of change in flows of aggregate resource consumption (energy, material and blue water). The latter group of consumption-based footprint indicators are estimated using environmental input-output analysis. We apply the biophysical accounts to four case study sites to evaluate and compare the sustainability of physical stocks and material/energy flows with respect to shares of planetary boundaries. The analysis integrates insights from the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015), steady-state economics (Daly, 1977; O'Neill, 2012) and environmental input-output analysis (Wiedmann et al., 2007; Miller and Blair, 2009).

Comparable biophysical accounts are compiled for four case study sites over a 15-year time period (1995–2009). The sites include two nations (Canada and Spain) and two sub-national regions (Nova Scotia and Andalusia). The national sites were chosen because Canada and Spain are both high-consuming countries with large environmental footprints, but they have followed significantly different development paths. Nova Scotia and Andalusia were chosen as sub-national case studies for two reasons. First, an empirical assessment of sub-national regions' proximity to a steady-state economy has not yet been attempted. Second, Nova Scotian and Andalusian performance is below their respective national averages in conventional economic indicators (i.e. gross domestic product) so we were interested to see if this finding would also be reflected in our analysis of physical stocks, flows and scale of economic activities.

The remainder of the article is structured as follows. Section 2 presents the biophysical accounting framework and environmental input-output model used to estimate the indicators of environmental pressure for each site. Section 3 describes the development of the stock, flow and scale indicators at national and sub-national levels. Section 4 reports the results including a comparative analysis that highlights the performance of each case study site in relation to steady-state conditions and describes the reductions in resource use needed to achieve a steady-state economy. Section 5 discusses implications of the results, limitations of the analysis and ideas for further research. Section 6 concludes.

2. Biophysical accounts and environmental input-output model

In this section, we begin by presenting the conceptual framework used to link (i) changes in economy-wide biophysical stocks and flows, and (ii) the sustainability of environmental pressures known to impact key Earth-system processes. Next, we discuss the construction of the environmental input-output (EIO) model that was used in this study.

2.1. Biophysical accounts

The biophysical accounts are organized following the method discussed in detail by O'Neill (2012) which is, in turn, based on Daly (1977) Ends-Means framework. In Daly's Ends-Means framework, items are organized hierarchically from *ultimate means* (the capacity of the environment to provide useful sources of matter-energy, and sinks to assimilate useless wastes) to *intermediate means* (the stocks of people, domesticated animals and built capital that transform flows of low-entropy matter-energy into goods and services) to *intermediate ends* (the social goals that the economy is expected to provide) to the *ultimate end* (that highest goal desired only for itself). The biophysical accounts described here measure the use of the means in the bottom two rungs of the Ends-Means hierarchy, whereas a separate set of social accounts would measure