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Methods

A dimensionally consistent aggregation framework for biophysical metrics

Deepak Malghan *

Centre for Public Policy, Indian Institute of Management Bangalore, Bannerghatta Road, Bangalore 560076, India

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ABSTRACT

We develop a formal representation of the economy–ecosystem interaction problem by distinguishing between stock-flow, and fund-flux spaces (Georgescu-Roegen, 1971). We then define dimensionless quantities in both the cardinal stock-flow space and the ordinal fund-flux space. This leads to analytic definitions of natural capital and natural income in the fund-flux space. We show that a stock-fund representation of the economy–ecosystem interaction problem helps investigate aggregation properties of biophysical metrics. In particular, we show how a metric that is dimensionally consistent in the stock-flow space can have dimensional problems in the fund-flux space. Ecological footprint is used as an illustrative example. Finally, we argue that dimensionally consistent metrics are keys to further the development of biophysical assessments as a tool for practical environmental policy.

1. Introduction

A key area of ecological economics research concerns the development of biophysical metrics that measure the physical size of economic activity. Popular metrics include ecological footprint (Rees, 1992; Wackernagel and Rees, 1996; Wackernagel et al., 2004); human appropriation of the products of photosynthesis (Rojstaczer et al., 2001; Vitousek et al., 1986); and aggregate material throughput metrics (Adriaanse et al., 1997; Gordon et al., 2006; Klee and Graedel, 2004; Matthews et al., 2000; National-Research-Council, 2004; Wernick and Ausubel, 1995). The central goal of these metrics is to determine if the scale of human activity is sustainable (Loh, 2002; Loh and Wackernagel, 2004; Wackernagel, 1999). Despite the increasing use of biophysical metrics in policy deliberations, there does not exist a consistent theoretical framework to study the aggregation properties of biophysical metrics, especially their dimensional consistency (Malghan, 2006; Mayumi and Giampietro, 2010).

Stripped of all (obviously important) details, any biophysical metric, Γ is an aggregation that can be represented as:

$$\Gamma = \sum_{i=1}^{n} \gamma_i \tag{1}$$

where Γ is the aggregate economic activity measured in some biophysical unit obtained by aggregating n different elemental sectors of the economy. For example, ecological footprint computes Γ as the sum of productive-area demanded by six key sectors of the economy (Wackernagel et al., 2004). The ultimate object of any biophysical assessment is to understand the relationship between aggregate human activity and the ability of the biophysical system to support and sustain it. Thus, apart from aggregating human activity, biophysical metrics also aggregate the 'ecological space' available to sustain it:

$$\Theta = \sum_{i=1}^{k} \theta_i \tag{2}$$

where Θ is the aggregate ecological space available. For example, in the case of ecological footprint, Eq. (2) takes the form of $H(t) = \sum_{i=1}^{k} P_i(t)$ where $H(t)$ is the sum-total of bioproductive land available obtained by aggregating k different types of land-area (Wackernagel et al., 2004). Given Γ and Θ, we can construct a scale metric, Ω that characterises the proportional relationship between the economy and the ecosystem:

$$\Omega = \mathbf{S}(\Gamma, \Theta) \tag{3}$$

where $\mathbf{S}$ is the 'scale function' (Malghan, 2006). Γ, Θ, and thus Ω are calculated at local, regional, national, and finally global levels. Indeed some of the biophysical assessments have even been used at the individual or household level (the footprint calculator for example). At every level of aggregation from the individual to the planet, Γ, Θ, and Ω are used as indices to track the progress of (biophysical) sustainability targets.

To serve as effective indicators of sustainability, any biophysical metric must consistently rank states of the world that it characterises

* Tel.: +91 80 2699 3355.
E-mail address: dmalghan@iimb.ernet.in.

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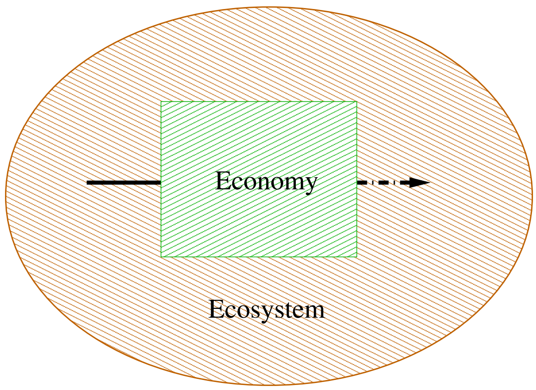

Fig. 1. A simplified representation of ecological economics' ontological vision. The throughput is represented by a solid line on the source-side and a broken line on the sink-side. This is consistent with the understanding that there is in general both a quantitative and qualitative transformation of the throughput (see Section 2.1 for a detailed explanation).

(Malghan, 2006; Mayumi and Giampietro, 2010). If we have $\Omega_i > \Omega_j$, what can we say about the corresponding states of the world? Does moving from Ω_i to Ω_j represent an improvement or a regression on society's sustainability goals? Formally, we ask: given $\Omega_i \lesseqgtr \Omega_j$, what can we say about $\Omega_i \succ \Omega_j$ ($\succ$ has the usual meaning: 'preferred to')? For example, if Ω represents a metric derived from biophysical assessments that aggregate material throughput (Adriaanse et al., 1997; Matthews et al., 2000), how do we rank two states of the world with $\Omega_i = 5$ and $\Omega_j = 3.5$? Is j more sustainable than i because $\Omega_i > \Omega_j$? Answering these questions requires us to look at the 'aggregation mechanics' that aggregated individual γs into Γ Eq. (1); θs into Θ Eq. (2); and finally properties of the scale function in Eq. (3). In this paper, we consider the first part of this larger consistency problem—the dimensional consistency of Γ and Θ. We investigate the dimensional consistency of aggregating on physical dimensions like mass (Adriaanse et al., 1997; Matthews et al., 2000); or area (Wackernagel et al., 2004).

The remainder of this paper is organised as follows: in the next section, we develop a stock-fund representation of the economy–ecosystem interaction problem. In Section 3 we develop definitions for dimensioned quantities in the fund-flux space. In particular, we develop working definitions for dimensionless quantities that are consistent across both stock-flow, and fund-flux spaces. In Section 4 we review the dimensional consistency of the ecological footprint, and conclude in Section 5.

2. Stock-Flow and Fund-Flux

We begin by developing a stock-fund representation of the economy–ecosystem interaction problem (Georgescu-Roegen, 1971; Malghan, 2006). Consider the elementary ontological picture of ecological economics—the economy as an open subsystem of the larger ecosystem that contains and sustains the economy (Fig. 1). The economy as an open subsystem is connected to the ecosystem through two different kinds of 'flows' that are fundamentally different from each other. The first flow is the familiar material throughput.[1] The throughput, as seen from Fig. 1 consists of two components: the source-side flow of raw material from the ecosystem into the economy, and the sink-side flow of waste products of the economy back into the ecosystem. This flow for example could be the throughput of timber from the forest into the economy; and discarded wood products (products of combustion if wood is used as a fuel) from the economy back to the ecosystem. The forest is not just a stock of timber but also provides important ecosystem services like micro-climate stabilisation. Unlike material flows however, there is no accounting identity that can describe how a 'flow' of micro-climate stabilisation service accumulates into some stock. Analytically intractable as they may be, ecosystem services are crucial to human existence (Costanza et al., 1997). There is of course a definite connection between the magnitude of throughput and ecosystem services like micro-climate stabilisation. If the aim of biophysical assessment is to understand the relationship between aggregate human activity and the ability of the biophysical system to support and sustain it, we need to understand (and quantify) this relationship between economy-generated throughput and ecosystem services.

If throughput is derived from a stock, ecosystem services are derived from a fund. Ecosystems that support the human economy are simultaneously both stocks and funds. A fund is a special configuration of a given stock of material(s) (Georgescu-Roegen, 1971; Malghan, 2006). For example a *special* configuration of a given stock of steel, aluminium, plastic, etc. constitutes the automobile which is a fund of transportation services. The operative words here are *special configuration*—the same stock of steel and aluminium in any other configuration cannot constitute a fund of transportation services. The most obvious example is an automobile that has met with an accident, and is on the way to a scrap-yard. Thus while simple conservation laws are sufficient to fully characterise the relationship between stocks and flows,[2] the relationship between a fund and ecosystem services derived from it are more complex, and characterised by laws that follow the spirit of the entropy law in thermodynamics.[3] Like an automobile, the ability of the forest to provide valuable services in its role as a fund is contingent on a particular configuration of the stocks that make up the forest. Moreover, the natural regeneration rate of the any constituent stock is dependent on the structure of the underlying fund-configuration. A captive plantation with the same standing-stock of timber as a forest with diverse species regenerates at a different rate *and* provides a different level of micro-climate stabilisation service. The service derived from a fund is not a physical flow like the throughput derived from the stock-function of the ecosystem. Services derived from the ecosystem in its role as a fund usually have very small 'rates of flow.' We use the term *service flux* to distinguish ecosystem services (derived from the fund-function of the ecosystem), from resource flows (derived from the stock-function).[4]

2.1. Stock-Fund Representation

In Fig. 2 we begin to develop an analytical representation of the stock-flow and fund-flux spaces that characterise economy-ecosystem interactions. $\dot{x}_i$ and $\dot{x}_o$ represent the throughput on the source-side and sink-side respectively. The throughput needs to be studied independently on the source-side and sink-side because the two flows are qualitatively and quantitatively different (Malghan, 2006). If wood from the forest is the source-side throughput, combustion

[1] In this paper, we illustrate our framework with examples of material throughput. Some of this discussion here is applicable to energy throughput with suitable modifications (Malghan, 2006).

[2] $x(\tilde{t}) = x(0) + \int_0^{\tilde{t}} (f_{in}(t) - f_{out}(t))dt$ where $f_{in}(t)$ is the flow into the stock at any time t and $f_{out}(t)$ is the outflow from the stock. $\tilde{t}$ is the current time period and $x(0)$ is the reference stock at time $t = 0$.

[3] Georgescu-Roegen (1971) in addition to providing the original exposition of the concept of fund also speculated on an entropy law modeled on the Second-Law of thermodynamics for matter. This so-called 'fourth-law' has been hotly contested (Cleveland and Ruth, 1997; Hammond and Winnett, 2009; Ayres, 1999, 1998). For our purposes here, it is sufficient to note that conservations laws (like the first-law of thermodynamics) alone cannot completely describe a fund, and we need to invoke some mechanism like the Second-Law that allows for qualitative degradation of energy *and* matter.

[4] The difference between resource flows and services on the time-dimension is crucial to understanding the difference between ecosystems as stocks and ecosystems as funds (Georgescu-Roegen, 1971, p.227; Malghan, 2006).