RESEARCH AND ANALYSIS

What Should Be Held Steady in a Steady-State Economy? Interpreting Daly's Definition at the National Level

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degrowth
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Summary

Within this article, I investigate a number of the conceptual issues that arise when attempting to translate Herman Daly's definition of a steady-state economy (SSE) into a set of national biophysical indicators. Although Daly's definition gives a high-level view of what would be held steady in an SSE, it also leaves many questions unanswered. How should stocks and flows be aggregated? What is the role of international trade? How should nonrenewable resources be treated? And where does natural capital fit in? To help answer these questions, I relate Daly's definition to key concepts and terminology from material and energy flow accounting. I explore topics such as aggregation, international trade, the relevance of throughput, and hidden flows. I conclude that a set of biophysical accounts for an SSE should include three types of indicators (stocks, flows, and scale), track how stocks and flows are changing over a 5- to 10-year period, use aggregated data that measure the quantity of resource use (rather than its quality), measure both total and nonrenewable resource use, adopt a consumption-based approach, include hidden flows, and exclude indicators that measure characteristics of the stock of natural capital (with the notable exception of indicators that measure the regenerative and assimilative capacities of ecosystems).

Introduction

Following the beginning of the global financial crisis in 2008, there has been increasing interest in economic models that do not rely on growth to improve quality of life. Within the past 6 years, there have been three international conferences on degrowth, and one on the steady-state economy (SSE), as well as a number of government-sponsored "beyond growth" events in countries such as Austria and France. The result is an emerging set of proposals on how to manage an economy without growth (e.g., Daly 2008; Dietz and O'Neill 2013; Jackson 2009; Latouche 2009; Victor 2008).

The idea of an SSE was largely developed by ecological economist Herman Daly in the 1970s, although it traces its roots as far back as the classical economists. It may be defined as a socioeconomic system where the main biophysical stocks and flows are stabilized and where material and energy flows are kept within ecological limits (Daly 1977, 1993, 1996, 2005). It is worth stressing that Daly's definition of an SSE is entirely biophysical. It does not refer to rates of gross domestic product (GDP) growth (or other socioeconomic variables for that matter).

The idea of degrowth is a bit more contentious, but has been defined as "an equitable downscaling of economic production and consumption that increases human well-being and enhances ecological conditions" (Schneider et al. 2010, 511). Advocates of degrowth tend to place more emphasis on social outcomes than their steady-state counterparts, as evidenced by the long list of social objectives included in the declaration from the first degrowth conference (Research & Degrowth

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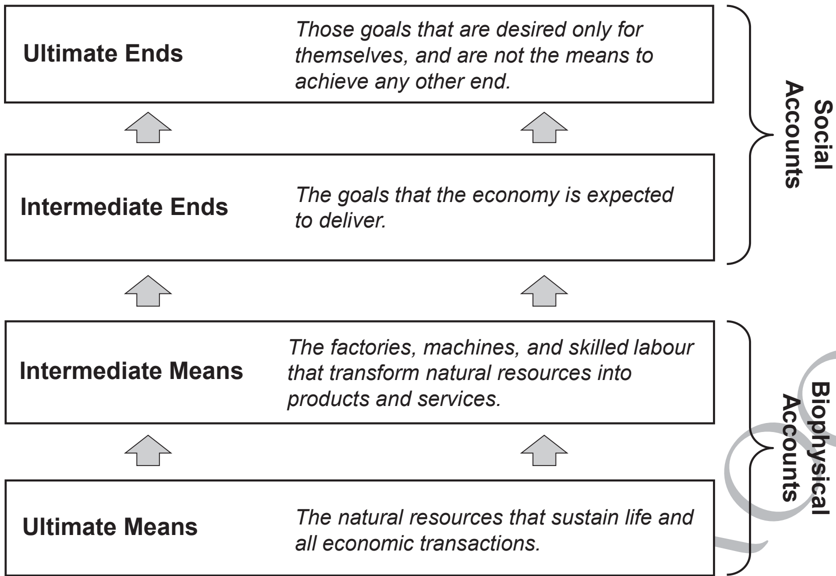

Figure 1 Conceptual framework for a set of indictors to measure how close national economies are to a socially sustainable steady-state economy. *Source*: Reprinted from *Ecological Economics*, Vol. 84, D. W. O'Neill, Measuring progress in the degrowth transition to a steady state economy, pages no. 221–231, Copyright 2012, with permission from Elsevier. Based on Daly (1977) and Meadows (1998).

2010). Nevertheless, the two concepts are seen by many as complementary. If resource use and waste emissions exceed ecosystem limits, then a process of degrowth may be needed before an SSE can be established (Kallis 2011; Kerschner 2010; Martínez-Alier 2009; Schneider et al. 2010).

In an earlier article, I analyzed four indicator approaches that could be used to measure how close modern economies are to a socially sustainable SSE (O'Neill 2012). I concluded that separate biophysical and social indicators represent the best approach, but a unifying framework based on ends and means is needed to choose appropriate indicators and interpret the relationships between them (figure 1). I proposed creating a set of biophysical indicators to measure how close countries are to Daly's definition of an SSE, as well as a set of social indicators to measure how well countries are doing on the social objectives described in the declaration from the first degrowth conference.

Within this article, I investigate a number of the conceptual issues that arise when attempting to translate the definition of an SSE into a set of biophysical indicators. These issues primarily relate to the construction of the *biophysical accounts* outlined in figure 1. To aid in my analysis, I relate Daly's definition to key concepts and terminology from material and energy flow accounting (MEFA). I divide the definition of an SSE into three separate components (stocks, flows, and scale). Following this, I investigate how to aggregate stocks and flows, whether renewable and nonrenewable resources should be treated differently, the role of international trade, the relevance of hidden resource flows, and the role of the stock of natural capital. Finally, I present a list of criteria that a set of indicators designed to measure how close countries are to an SSE should aim to satisfy.

Defining a Steady-State Economy

Herman Daly's definition of an SSE has evolved somewhat over time. Although all of his definitions contain the same basic elements, earlier definitions (e.g., Daly 1977, 1993) tend to focus more on the idea of *constant stocks*, whereas more recent definitions (e.g., Daly 1996, 2008) focus more on *constant flows*. Daly acknowledges this evolution in one of his more recent definitions:

> Following Mill we might define a SSE 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 . . . Alternatively, and more operationally, we might define the SSE in terms of a constant flow of throughput at a sustainable (low) level, with population and capital stock free to adjust to whatever size can be maintained by the constant throughput beginning with depletion and ending with pollution. (Daly 2008, 3)

In general, all of Daly's definitions contain three basic components: *stocks* (the physical size of the economy); *flows* (the throughput required to support the economy); and *scale* (the size of the economy in relation to the environment). There are three stocks that are relevant to the definition: the stock of built capital (e.g., buildings, transportation infrastructure, machinery, and durable goods); the stock of people (i.e., the human population); and the stock of domesticated animals (i.e., livestock). There are three flows that are relevant: the flow of material inputs from the environment to the economy; the flow of material outputs from the economy back to the environment; and the energy used by the economy. And, finally, there are two measures of scale that are relevant: the

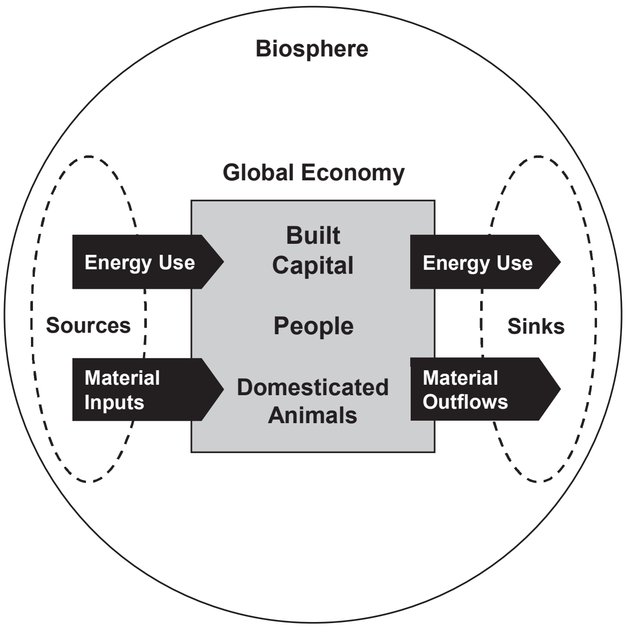

Figure 2 Stocks, flows, and scale quantities that relate to Daly's definition of a steady-state economy. Stocks are shown within the gray box representing the economy, flows are shown as arrows, and scale may be visualized as the relationship between arrows and dashed ovals. Source: Reprinted from *Ecological Economics*, Vol. 84, D. W. O'Neill, Measuring progress in the degrowth transition to a steady state economy, pages no. 221–231, Copyright 2012, with permission from Elsevier. Based on Goodland (1991, 17).

ratio of material inputs to the capacity of ecosystem sources to regenerate materials and the ratio of material outflows to the capacity of ecosystem sinks to assimilate wastes (figure 2).

I propose three definitional distinctions based on these quantities. If an economy manages to stabilize the stocks and flows pictured in figure 2, then I refer to it as a *stable economy*. If the economy also manages to maintain material flows within ecological limits, then I refer to it as a *steady-state economy*. If, in addition to these biophysical criteria, the economy achieves a high quality of life for its citizens, then I refer to it as a *socially sustainable steady-state economy*.

In practice, it is unlikely that a country would manage to stabilize all relevant stocks and flows concurrently. Boulding (1975, 92) writes that "All stocks . . . do not have to be stationary at the same time, and we can postulate a number of quasi-stationary states in which some elements of the system are stationary while others are not." Presumably, though, the more stocks and flows that were stabilized, the closer a given economy would be to an SSE.

It may turn out that certain quantities, such as the stock of built capital, are too difficult to measure or are adequately captured by other indicators. Nevertheless, I would urge a certain amount of caution in excluding these quantities. The environmental pressure exerted by a growing stock of built capital may be adequately captured by flow indicators, but, at the moment, we do not have the necessary data on stocks to test this hypothesis. There is, however, an emerging body of literature on the measurement and modeling of physical stocks (e.g., Matthews et al. 2000; Müller 2006; Pauliuk and Müller 2014). An accounting system that tracked changes in stocks, as well as changes in flows, would allow a number of potential relationships to be investigated.

It is worth pointing out that both material and energy flows are included in Daly's definition of an SSE. Although material flows may seem to have more obvious environmental impacts, energy flows should not be ignored. Physically speaking, energy is the ability to do work. Environmentally speaking, it has been called the "master resource" (Simon 1996, p. 162). Our ability as a species to modify our environment is directly related to the amount of energy we have at our disposal. Although different sources of energy (e.g., coal, nuclear, hydro, and wind) have different environmental impacts, all else being equal as we use more energy we also use more materials, produce more wastes, and modify the landscape to a greater extent. As Paul Ehrlich and colleagues put it:

> [N]o way of mobilizing energy is free of environmentally damaging side effects, and the uses to which energy from any source is put usually have negative environmental side effects as well. Bulldozers that ran on hydrogen generated by solar power could still destroy wetlands and old-growth forests (Ehrlich et al. 1997). Q3

Finally, it is worth touching on just how long stocks and flows need to remain stable for an economy to be considered an SSE. There is a difficult trade-off here. On the one hand, the time period needs to be long enough for us to be confident that the various biophysical quantities are indeed stable. From an ecological perspective, this might mean a human generation or more. On the other hand, if we are trying to manage the national economy and direct it toward an SSE, then we cannot afford to wait 20 years to see whether a given set of policies is working. Current economic aggregates that are used to manage the economy (e.g., GDP) are produced on a quarterly basis, whereas biophysical aggregates (e.g., domestic material consumption; DMC) tend to be calculated annually. To observe any kind of meaningful trend probably requires at least five data points, so I would argue that at least 5 years of biophysical data are needed to assess whether a country is stabilizing its resource use. In practice, though, it is not just the number of data points that is important, but how well a trendline fits these data points. A decade or more of clearly trending data may be needed to confidently describe an economy as an SSE.

The Issue of Aggregation

Daly (1996, 31) states that, in an SSE "aggregate throughput is constant," but he does not specify how this aggregation should be performed. There are a number of possible ways that stocks and flows could be aggregated, such as by weight, volume, area (e.g., ecological footprint), energy content, or monetary value. Victor (2009) is critical of these simple methods, however, claiming that aggregation in monetary terms is not consistent with Daly's biophysical definition of an SSE, and that aggregation in physical terms overlooks important differences in the composition of stocks and the environmental impact of flows. Van den Bergh (2011) makes a similar objection against using simple aggregated indicators to measure degrowth. He writes:

> [O]ne should be careful with the precise definition of physical degrowth. We certainly do not want to focus on reducing some simplified, aggregate measure of total tons of materials and substances in the economy (whether stocks or flows). Not everyone agrees with this—witness the popular notions of factor X (X = 4, 10, etc.), MIPS, ecological rucksack and TMR promoted by the Wuppertal Institute. Counting total material flows is a nice pastime activity, but we should instead be concerned with environmentally relevant substances/materials and assign these appropriate weights in any aggregation process. All in all, it is not clear what aggregate physical quantity should exactly degrow—there is a measurement or indicator problem here. (Van den Bergh 2011, 884)

These critiques raise an important question: What is the main objective of an SSE? Is it to reduce environmental *impact* or environmental *pressure*? The distinction between these two concepts is made in the DPSIR indicator framework used by the European Environment Agency (EEA). DPSIR is a causal framework for describing the interactions between society and the environment, categorizing these as driving forces, pressures, states, impacts, and responses. According to the DPSIR framework, social and economic developments exert pressure on the environment, and, as a consequence, the state of the environment changes. This change leads to impacts that may (or may not) elicit a societal response. Pressures include the use of resources, the emission of wastes, and the use of land. Impacts refer to changes in the functioning of the environment, including changes to ecosystem health, resource availability, and biodiversity (EEA 2003).

The implicit suggestion made by Victor (2009) and Van den Bergh (2011) is that the focus of an SSE should be to reduce and stabilize environmental impact. However, I would argue that the goal of an SSE is to reduce and stabilize environmental pressure. Conventional environmental policy is failing to solve major environmental problems, such as climate change and biodiversity loss, because it does not address the driving forces and pressures that are causing these problems (Haberl et al. 2009; Spangenberg 2007). An SSE attempts to reduce the pressure on the environment by limiting the aggregate quantity of material and energy use, thus making environmental policy objectives more achievable. The objective of an SSE is not to solve problems related to the quality (or composition) of resource use. Issues relating to the substitution of specific materials for one another are the role of conventional environmental policy, which would still be needed in an SSE. The objective of an SSE is to address the overall scale of the production and consumption system—to hold *quantity* steady while allowing *quality* to improve—and, for this purpose, I believe that highly aggregated indicators that measure environmental pressure are appropriate.

The simplest interpretation of Daly's definition would therefore measure stocks and flows in terms of their basic physical magnitudes (i.e., mass and energy content). In fact, Neumayer (2010) claims that the concept of material flow accounting (MFA) was inspired by Daly's definition of an SSE and his "emphasis on the growing scale or material throughput of the economy as the main cause of environmental degradation" (Neumayer 2010, 175). While not without limitations, aggregate material use is a well-established indicator of environmental pressure. As Krausmann and colleagues (2009) write:

> Clearly, the environmental pressures and sustainability problems associated with the extraction and use of materials are extremely heterogeneous. They differ largely by material and vary over time with technological change. Aggregate materials use indicators . . . cannot capture the full environmental effect of shifts in the composition of materials use or of technological fixes. But even though there is no simple one to one relation between aggregate materials use and environmental deterioration, the size and composition of materials use serves as a proxy for environmental pressures resulting from human activities. (Krausmann et al. 2009, 2703)

Moreover, there is empirical evidence to support the notion that larger aggregate resource use leads to greater environmental impacts. Environmentally weighted material consumption (EMC) is an indicator that aims to measure the total environmental impact of material flows. To calculate this indicator, mass data from material flow accounts are multiplied by environmental impact data from life cycle assessment studies. Based on an EMC study conducted in the Netherlands, Van der Voet and colleagues (2004) find that while the mass flows of an *individual* material are not indicative of its environmental pressure, the same is not true when materials are aggregated. They write: "On a more aggregate level of groups of materials, mass-based and impact-based indicators appear to point in the same direction. At the least, therefore, the relevancy of the mass-based indicators cannot be dismissed easily" (Van der Voet et al. 2004, 134).

Based on a larger study of 28 European countries, Van der Voet and colleagues (2005, 69) conclude that there is a "rather high" degree of correlation between aggregate material flows (as measured by DMC) and aggregate environmental impact (as measured by EMC). The correlation coefficient between the two quantities is 0.73, indicating that approximately 53% of the variation in EMC is explained by DMC and vice versa. Therefore, the use of environmental pressure indicators, such as the total weight of material flows, may also go some way toward satisfying the environmental impact agenda articulated by authors such as Victor (2009) and Van den Bergh (2011). Such indicators also have the advantage of being more transparent than environmental impact indicators.

Although aggregation might seem to be less of an issue for energy flows than material flows, a number of methods for aggregating energy from different sources do exist. Given that all forms of energy can be converted to heat, the simplest aggregation method involves adding up energy flows in terms of their heat content. The advantage of the heat content approach is that it uses a simple, well-defined accounting system based on the conservation of energy, and the heat contents of fuels are easily measured (Cleveland et al. 2000). The heat content approach does not, however, take into account qualitative differences between different energy carriers. The method implicitly assumes that "all Joules are equal," although, from a socioeconomic perspective, they may not be.

In order to account for differences in energy quality, alternative measures, such as *exergy*, have been devised. Exergy measures the maximum amount of useful work that could theoretically be performed by a given amount of energy. Whereas energy is always conserved in any process (this is the first law of thermodynamics), the same is not true of exergy. Exergy is not conserved, but is partially "used up" in any transformation (Ayres and Warr 2009). The main reason to consider using an approach that takes energy quality into account would be to link socioeconomic performance to a physical measure of resource use. This was the objective of a study by Ayres and Warr (2009), for example, who were able to explain past U.S. economic growth using a production function that includes capital, labor, and exergy and which does not require the exogenous technological progress factors used in conventional models.

Although it is hoped that a better understanding of economic systems will be obtained by analyzing the relationships between biophysical and social indicators, such an analysis is not the primary purpose of the indicators in the *biophysical accounts*. The primary purpose of these indicators is to determine how close national economies are to an SSE. In this context, it is not important whether energy is being used to perform useful work, or squandered as waste heat, given that both of these processes exert pressure on the environment. Thus, as with material flows, I would argue that energy flows should be aggregated in terms of quantity (i.e., heat content in Joules), as opposed to quality.

Renewable and Nonrenewable Resources

A related issue that is worth considering is whether renewable and nonrenewable resource flows should be treated differently in the definition of an SSE. Daly's three principles for sustainable resource use provide some guidance. These principles state:

1. Limit the use of all resources to rates that ultimately result in levels of waste that can be absorbed by the ecosystem.
2. Exploit renewable resources at rates that do not exceed the ability of the ecosystem to regenerate the resources.
3. Deplete nonrenewable resources at rates that, as far as possible, do not exceed the rate of development of renewable substitutes. (Daly 1990, 2005)

The principles imply that it is necessary to distinguish between renewable and nonrenewable resources entering the economy, given that the rules for their sustainable use are different. Whereas an SSE implies a constant rate of total resource use, maintained within the regenerative capacity of ecosystems, it effectively implies a declining rate of nonrenewable resource use if the economy is to be sustainable in the long run.

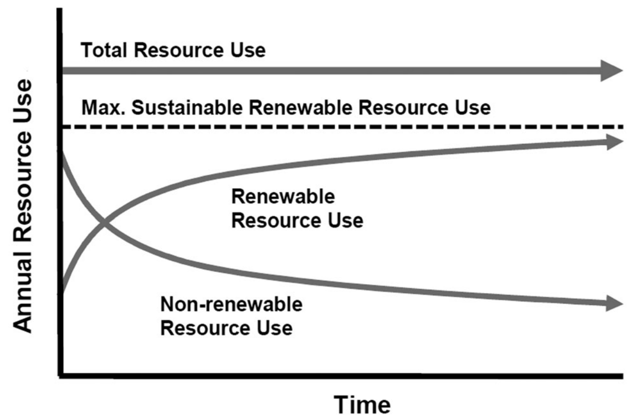

Figure 3 Resource use in an economy that satisfies both the stability and scale criteria (on the input side) for a steady-state economy. Max. = maximum.

Q4

However, it is important not to confuse the stability of resource flows with their scale. I would characterize an economy with a constant level of total resource use (i.e., renewable plus nonrenewable) as a *stable economy* and one worth being able to identify. In such an economy, the resource flow available to meet society's needs would be constant, as would the level of pressure exerted by the economy on the environment (all else being equal). A stable economy would not necessarily be sustainable, however, unless the rate of renewable resource use was kept within the regenerative capacity of ecosystems, and the rate of nonrenewable resource use decreased over time. Resource use in such an economy might resemble the scenario depicted in figure 3.

It is worth noting that if (1) total resource use is constant and (2) nonrenewable resource use is decreasing at a rate of X% per year, then renewable resource use must be increasing at X% per year. In other words, conditions 1 and 2 are effectively equivalent to Daly's third principle of not depleting nonrenewable resources faster than renewable substitutes can be developed.[1] Perhaps more important, these two conditions are also easier to measure.

As Krausmann and colleagues (2009) show, global economic growth has been associated not only with rising material use, but also with a shift from renewable to nonrenewable resource use. In an SSE, this trend would need to be reversed. However, the substitution of nonrenewable resources by renewable resources could cause renewable resource use to increase further beyond the regenerative capacity of ecosystems. Some researchers, such as Haberl and colleagues (2007), already caution about the limited possibility of substituting renewable resources, such as biomass, for nonrenewable resources, such as fossil fuels. Renewable resource extraction may not be sustainable if it jeopardizes ecosystem services or biodiversity. Thus, it seems likely that degrowth in total (i.e., renewable

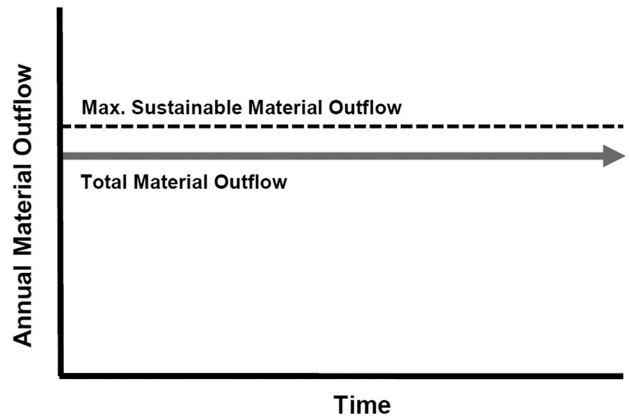

Figure 4 Total material outflow in an economy that satisfies both the stability and scale criteria (on the outflow side) for a steady-state economy. Max. = maximum.

plus nonrenewable) resource use will be needed in order to achieve an SSE that can be maintained over the long term.

On the outflow side, it is not particularly important whether wastes come from a renewable or a nonrenewable source. It is more important to distinguish where these materials are deposited (e.g., in land, water, or air). As with inflows, the stability of outflows remains an important criterion for ensuring that environmental pressure does not increase over time. However, the most important issue is for total outflows to remain within the assimilative capacity of ecosystems (figure 4).

The Issue of Trade

In order to make the case for an SSE, Daly and others often use a figure showing the global economy embedded within the biosphere (see figure 2). Though this global picture is useful for describing the basic idea of an SSE, it is not sufficient for describing an SSE at the national level. A definition of an SSE at the national level is needed because economic policy is not managed globally, but nationally.

The methods and terminology of MEFA are particularly useful for exploring some of the different ways that an SSE could be defined at the national level. MEFA is a framework for analyzing the flow of physical inputs into an economy, the accumulation of stocks within the economy, and the flow of physical outputs to other economies or back to nature (Haberl et al. 2004). It is based on the concept of *social metabolism* (Ayres and Simonis 1994; Fischer-Kowalski 1998), which views an economy as a metaphorical organism that functions by appropriating materials and energy from the environment and returning these back in an altered form. The MEFA framework includes established standards of MFA (Eurostat 2001, 2007) and proposed methods of energy flow accounting (EFA) (Haberl 2001).

Figure 5 shows the physical flows between a national economy, its environment (i.e., national territory), and the rest of the world. It introduces a number of quantities that are drawn from MEFA, which I use to illustrate some of the general issues surrounding trade. With respect to materials, these quantities include:

- *Domestic material extraction* (DME): The raw materials that are extracted from within a country's borders and used as material inputs to the national economy.
- *Material imports* (I_M): Products at all stages of processing (from basic commodities to highly processed goods) that are imported and used in the national economy.
- *Direct material input* (DMI): All materials, whether extracted in the national territory or imported, that enter the national economy for further use in production or consumption processes.
- *Domestic processed output* (DPO): The outflow of waste materials that are released back into the national territory after having been used in the national economy.
- *Material exports* (X_M): Products at all stages of processing that are exported from the national economy.
- *Direct material output* (DMO): All materials, whether wastes or exports, that leave the national economy.

In general, for each of the above material flow quantities, there is a corresponding energy flow quantity drawn from EFA. Domestic energy extraction (DEE) parallels DME, energy imports (I_E) parallel I_M, and so on.

It seems reasonable that for a national economy to be called an SSE, the stock of built capital, people, and domesticated animals within its physical borders should be stable over time. However, exactly which flows should remain constant, and what sources and sinks they should be compared to, is not so clear. Below, I discuss four possible options for defining a national SSE. The first of these ignores trade, whereas the other three include it. The four options are: (1) stable domestic extraction and domestic outflows; (2) stable direct inputs and direct outputs; (3) stable consumption; and (4) stable throughput. Note that the important issue of whether to include hidden flows in the definition of an SSE is discussed separately in a later section.

Stable Domestic Extraction and Domestic Outflows

The first option would be to define an SSE in terms of the material and energy extracted within a country's borders and the wastes released within its borders. In other words, to define it based on stable DME, DEE, and DPO. Trade (i.e., imports and exports) would be completely ignored.

In this approach, the scale of economic activity in relation to ecosystem capacity could be calculated on the input side by comparing DME to sources within the country's borders. On the output side, scale could be calculated either by comparing DPO to national sinks (e.g., for pollutants remaining within the country's borders) or by comparing it to some assigned share of global sinks (e.g., for pollutants crossing national borders, such as carbon dioxide).

The main problem with the domestic extraction and outflows approach, however, is that a country could be importing a large and increasing volume of materials and energy and still be considered an SSE if domestic extraction were not increasing.

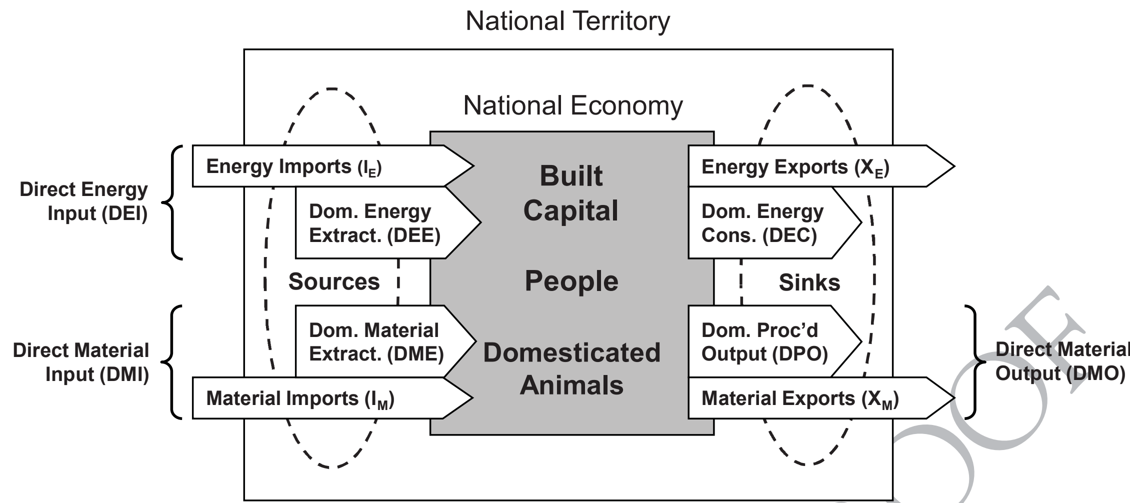

Figure 5 Stocks, flows, and scale relationships for a national economy, taking international trade into account. Dom. = domestic; Proc'd = processed; Extract. = extraction; Cons. = consumption. Q5

If the goods consumed in the country were produced abroad, then the waste outflows generated during their production would not be counted in the importing country's accounts either. Given the increasing shift of manufacturing from developed to developing countries, a national SSE definition based solely on domestic extraction and domestic outflows would favor developed countries and seemingly allow them to skirt responsibility for the environmental impact of their resource consumption. It is debatable whether such an approach would really capture what is meant by an SSE.

Stable Direct Inputs and Direct Outputs

The second option would be to define an SSE in terms of all of the material and energy inputs entering the economy (whether extracted domestically or imported) and all of the material outputs leaving it (whether as wastes or as products for export). In other words, to define it based on stable DMI, direct energy input (DEI), and DMO. In general, the relationship between the quantities discussed thus far (and shown in figure 5) is (equations 1–3):

$$\text{DMI} = \text{DME} + I_M \quad (1)$$

$$\text{DEI} = \text{DEE} + I_E \quad (2)$$

$$\text{DMO} = \text{DPO} + X_M \quad (3)$$

where I_M is material imports, I_E is energy imports, X_M is material exports, and X_E is energy exports.

What is accounted for in this approach is the total amount of material and energy entering the national economy (regardless of where it comes from) and the total amount of material leaving the economy (regardless of where it goes). With this approach, a country could reduce its domestic extraction, while increasing imports, and still remain an SSE. Similarly, it could emit less waste domestically, and export more products to other countries, and still remain an SSE.

A potential problem with the direct input/output approach, however, is that the resource flows accounted for may not necessarily benefit the people living in the country in question, and therefore it is debatable whether they should be held responsible for these flows. Resources could be extracted within a country's borders, but then exported (i.e., sold and consumed elsewhere). Or, resources could simply pass through the economy, first being imported and then re-exported (the so-called Rotterdam effect). Moreover, the approach results in double counting, given that a raw material imported into country A but exported to country B as a finished product would be counted as an input to both economies. Whereas DMI, DEI, and DMO could be used to assess the stability of total material and energy flows entering and leaving a particular economy, they could *not* be used to assess the scale of economic activity in relation to ecosystem capacity owing to this double counting problem. Separate indicators (such as those described in the previous section) would still be needed to assess scale.

Stable Consumption

The third option would be to define an SSE using a consumption-based approach. If the economy is viewed as a system for transforming natural resources into human well-being (as the ends-means framework shown in figure 1 suggests), then it may make more sense to account for resource use according to who benefits from the resources—in other words, by who consumes them. Following the standards of MEFA, material and energy consumption indicators may be defined as follows (equations 4 and 5):

$$\text{DMC} = \text{DME} + (I_M - X_M) = \text{DPO} + \text{NAS} \quad (4)$$

$$\text{DEC} = \text{DEE} + (I_E - X_E) \quad (5)$$

where DMC is *domestic material consumption*, DEC is *domestic energy consumption*,[2] and NAS is *net additions to the stock of built capital*. DMC represents the flow of material inputs to a given economy that are either converted into wastes by the economy or accumulate as stocks within the economy. Given that all stocks will eventually turn into emissions and wastes at some point in time, Weisz and colleagues (2006) note that DMC may also be interpreted as an indicator of the waste potential of a national economy.

In practice, material consumption indicators such as DMC are normally calculated in input units (i.e., as tons of biomass, minerals, and fossil fuels entering the economic system). These data could be compared to some assigned share of global sources to arrive at a measure of economic activity in relation to ecosystem capacity—on the input side at least. However, material consumption indicators such as DMC could not be meaningfully compared to national or global sinks because only part of what is counted as consumption enters the waste stream in a given year (the rest accumulates as a stock). Therefore, a material outflow indicator (such as DPO) would still be needed to construct a measure of scale on the output side

Although a consumption-based approach might seem to be an improvement on the purely territorial approach discussed above, there are still some sticky issues. A country could have low and stable levels of consumption, but extract a high and increasing volume of resources. If these resources were exported, they would not be counted in the accounts of the extracting country. They would, instead, be counted in the accounts of the country where they were consumed. The intention of a consumption-based approach is to assign the responsibility for a given resource flow to the people who benefit from that flow. However, it could be argued that the extractors of a resource also benefit from the flow produced because they earn an income when they export it. It is therefore tempting to propose some form of shared responsibility between extractors and consumers (e.g., Lenzen et al. 2007). However, I would argue that the extractors do not actually benefit until they spend their income. Only then are they receiving goods and services in return for the resources that they have extracted.

Stable Throughput

The fourth, and final, option would be to define an SSE in terms of stable *throughput*. Daly often uses this term when defining an SSE, which lends some weight to using a throughput measure. However, it is difficult to know whether Daly is using the term in the technical sense that is used in MFA or as shorthand for some other quantity.

From an MFA perspective, throughput is the flow of matter or energy that goes *through* the economy within a certain period of time—generally the accounting period of 1 year. Eurostat (2001) proposes a method of defining and calculating material throughput (MT) that equates throughput to DMI minus net additions to stock (equation 6):

$$\begin{aligned} MT = DMI - NAS &= (DME + I_M) - NAS \\ &= DPO + X_M = DMO \end{aligned} \tag{6}$$

The corresponding relationships for energy throughput (ET) would be (equation 7):

$$ET = DEI = DEE + I_E = DEC + X_E \tag{7}$$

These relationships are shown in figure 6. Both throughput measures are equivalent to quantities that have already been presented and discussed. MT is equivalent to DMO, and energy throughput is equivalent to DEI.

Daly speaks of ensuring that throughput is "within the regenerative and assimilative capacities of the ecosystem" (Daly 2008, 3). However, MT (as defined above) cannot be directly compared to the regenerative and assimilative capacities of ecosystem sources and sinks. Comparing MT to either sources or sinks would result in double counting given that exports are not subtracted from imports. Moreover, throughput omits flows from nature that accumulate as stocks, making it incomparable with ecosystem sources. In short, MT is not directly comparable to ecosystem sources and sinks because—by Eurostat's (2001) definitions at least—MT does not include all of the flows between the economy and the environment.

Daly appears to have a somewhat looser interpretation of the meaning of throughput than the one shown in figure 6. He writes:

> Throughput is the entropic physical flow of matter-energy from nature's sources, through the human economy and back to nature's sinks; it is necessary for maintenance and renewal of the constant stocks . . . But throughput is not itself capable of directly yielding service. It must first be accumulated into a stock of artifacts; it is the stock that directly yields service. Stocks may be thought of as throughput that has been accumulated and "frozen" in structured forms capable of satisfying human wants. (Daly 1993, 326–327)

Daly appears to consider MT to be any material input that eventually becomes a material outflow, regardless of how long the material is captured as a stock in the economy. In the language of MFA, Daly's quantity is not really MT, but either DMI or DMC. Which one, of course, depends on how exports are treated in an SSE—a topic that Daly does not discuss.

Which Approach to Choose?

In the sections above, I have discussed four possible options for defining a national SSE. I propose adopting a consumption-based approach for three main reasons:

1. A consumption-based approach assigns responsibility for resource flows to those who benefit from using the resources.
2. A consumption-based approach helps to link together the indicators in the ends–means framework (figure 1).

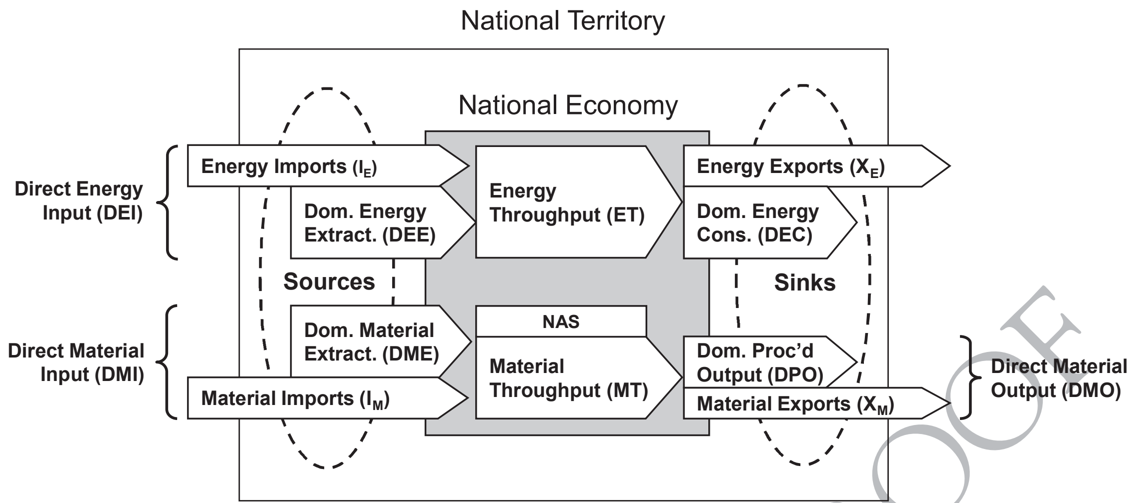

Figure 6 Definition of material and energy throughput. NAS = net additions to the stock of built capital; Dom. = domestic; Proc'd = processed; Extract. = extraction; Cons. = consumption.

If there is any relationship between resource use and social performance, then a consumption-based approach would be the most likely approach to reveal it.

3. A consumption-based approach allows for greater consistency between the indicators that are used to measure the stability of flows and those that are used to measure the scale of economic activity in relation to the capacity of ecosystem sources and sinks.

That said, there is undoubtedly value in complementing consumption indicators with territorial measures (e.g., domestic extraction and domestic outflows) to ensure that countries are held accountable for the activities that take place within their own borders. Though international demand may drive resource extraction in a country, it is still up to that country whether they choose to extract and sell their national resources and which methods and technologies they employ.

Hidden Flows

The gray box shown in figure 5 illustrates the system boundary between a national economy, its territory, and the rest of the world. The flows that enter the economy are referred to as *used extraction* in MEFA because they are used to produce the goods and services consumed, and they are ascribed economic value. Not all used extraction is accounted for in indicators such as DMC, however. Although DMC includes the raw materials that are extracted from within the national environment, as well as the products that are imported minus those that are exported, it does not include the upstream resource requirements associated with imports and exports (so called *embodied flows*). These flows are accounted for in other indicators, such as *raw material consumption* (RMC), however, which accounts for all raw materials required to satisfy a country's final demand for goods and services, regardless of where the materials are extracted from.

Wiedmann and colleagues (2013) show that the choice of whether to include embodied flows can change whether or not nations are observed to be achieving an absolute reduction in resource use. Although decoupling between GDP and DMC has been observed in a number of countries, this is not the case when RMC is calculated and embodied flows are accounted for. Consumption-based indicators that account for the energy and materials embodied in trade may help resolve important debates on the linkage between economic activity and resource use.

Materials and energy may also be extracted from the environment without ever entering the economy. Examples include soil and rock that are excavated during construction, biomass that is killed but not harvested (e.g., discarded by-catch and wood harvesting losses), and overburden from mining and quarrying. These flows are referred to as *unused extraction* in MEFA, and they can occur in either the country under consideration or its trading partners. If unused extraction is added to RMC, the result is referred to as *total material consumption* (TMC). Empirical studies show that unused extraction can be very large. For example, data from the Global Material Flows Database (SERI, 2010) Q6 suggest that unused extraction accounts for approximately 40% of global material extraction.

An important issue to consider is whether or not these two types of hidden flows (embodied flows and unused extraction) should be included in the definition of an SSE. It seems relatively clear that if trade is to be considered at all, then the embodied material and energy flows needed to produce the traded products should be included. Measures of apparent consumption such as DMC are, in effect, inconsistent accounting quantities that favor foreign production over domestic production. Wiedmann and colleagues (2013) show that the upstream flows associated with traded products are three times larger than the physical flow of products themselves. Without an indicator such as RMC, it is not possible to tell whether developed countries are offshoring their pressure on the environment to developing countries.

The question of whether to include unused extraction is a bit trickier. On the one hand, it seems reasonable to draw a hard boundary between the economy and the environment and exclude unused flows because they do not cross this boundary. If the economy is viewed as a system for transforming natural resources into human well-being (as the ends-means framework shown in figure 1 suggests), then the *biophysical accounts* should include only those resources that actually enter the economic system. Flows that enter the economic system are transformed into goods and services and therefore have the potential to contribute to the intermediate and ultimate ends of the economy, whereas unused flows do not. In short, if the objective is to create a system of accounts that sheds light on the social implications of different patterns of resource use, then it would be more appropriate to measure used extraction than total extraction.

However, there is also a strong argument to be made for including unused flows in the definition. Unused flows are a by-product of economic activity, and they exert a pressure on the environment. Omitting unused flows could result in an artificially low estimate of the scale of economic activity in relation to what ecosystems can support. For example, the used extraction of biomass (e.g., fish capture) might be lower than the maximum sustainable yield, but the total extraction of biomass (including by-catch as well) might be higher. Moreover, unused extraction may grow larger over time as we deplete the more accessible resources. Leaner ores with more slag and overburden may replace richer mines as they become exhausted. In short, if the objective is to create a system of accounts that assesses environmental sustainability, then unused flows should be included.

Given that the primary objective of the *biophysical accounts* is to measure how close countries are to an SSE, and sustainable scale is a critical part of the definition of an SSE, I would argue that unused flows should ideally be included in the accounting system (although I acknowledge that they are difficult to measure in practice).[3] This does not necessarily imply that unused flows should be included in all applications to which the accounting system is put, however. When examining the relationship between resource use and social performance, it may be more appropriate to exclude unused flows.

Natural Capital

An SSE is defined as an economy in which the stocks of built capital, people, and domesticated animals—and the material and energy flows required to support them—are held constant, and where these flows are kept within ecological limits. But what is the role of the stock of natural capital in this definition?

Daly and Farley (2004, 17) define natural capital as "a stock that yields a flow of natural services and tangible natural resources. This includes solar energy, land, minerals and fossil fuels, water, living organisms, and the services provided by the interactions of all of these elements in ecological systems." Although the stock of natural capital generates a flow of natural resources that enter the economic system, I would argue that the stock of natural capital itself lies outside of the system boundaries of the economy. One of the main reasons for establishing an SSE is to preserve the stock of natural capital, which is seen as complementary to the stocks within the economic system (and necessary for their maintenance). The hope is that by stabilizing the scale of the economic system, the stock of natural capital, and the services that it provides, can be maintained.

I would therefore argue that indicators relating to the stock of natural capital itself should not necessarily be included in an accounting system for an SSE, with the notable exception of indicators that measure the regenerative and assimilative capacities of ecosystems. These latter indicators are required to determine whether the scale of material flows between the environment and economy is sustainable—one of the main criteria for an SSE.

This is not to say that there is no value in developing an accounting system to monitor changes in the stock of natural capital and the services provided by it—clearly there is. Indicators that measure natural capital could, for example, be compared to biophysical indicators that measure the size of the economy to test whether an increase in the size of the economy results in a decrease in natural capital (as the concept of *strong sustainability* predicts; see Neumayer [2010]). However, an accounting system for natural capital would be complementary to the one I have proposed, which focuses on the biophysical requirements and social performance of the economic system.

Conclusions

The definition of an SSE developed by Daly (1977, 1993, 1996, 2008) provides a high-level description of what would be held steady in an SSE, but it also leaves a number of questions unanswered. This article has discussed some of the ways that specific aspects of the definition could be interpreted, with the eventual aim of developing a set of biophysical indicators capable of measuring what is meant by an SSE. Biophysical accounting has come a long way over the past two decades, both in terms of producing physical accounts within whole-economy models (e.g., Turner et al. 2011) and in turning monetary input-output accounts into physical accounts (e.g., Wiedmann et al. 2013). Measuring how close national economies are to biophysical stability is now possible, but indicators must be chosen carefully. Based on the discussion in this article, I suggest that a system of *biophysical accounts* designed to measure progress toward a national SSE should:

- Include indicators for the three main components of the definition (stocks, flows, and scale)
- Show how stocks and flows are changing over a sufficiently long time period (5 to 10 years)
- Use aggregated indicators that measure the *quantity* of resource use (as opposed to its quality)
- Adopt a consumption-based approach, but also track territorial measures
- Measure total (i.e., renewable plus nonrenewable) resource use and nonrenewable resource use

- Include hidden flows where possible (in particular, embodied flows)
- Leave out indicators that measure characteristics of the stock of natural capital, with the notable exception of indicators that measure the regenerative and assimilative capacities of ecosystems

There are undoubtedly other ways that the definition of SSE could be interpreted than what I have put forward. Other interpretations might draw the system boundary in a different way (e.g., attaching less importance to what is happening to the stock of built capital and more importance to what is happening to the stock of natural capital). Nevertheless, I believe that my interpretation is a reasonable one that helps resolve a number of outstanding issues and allows an operational set of indicators to be constructed.

These indicators would help define the quantities that should be held steady in an SSE—a relatively small list of biophysical stocks and flows. Of course, a great many things would *not* be held constant in such an economy and could be encouraged to develop and improve. These include human well-being, equity, democratic institutions, social capital, technology, and culture.

The establishment of an SSE would greatly reduce the pressure on ecosystems by limiting the quantity of resource use. However, an SSE would not solve problems related to the quality (or composition) of this resource use. Even in a world where aggregate resource use was constrained, conventional environmental regulation would still be needed to limit the use of harmful substances, protect species at risk, maintain soil fertility, and manage land-cover change. In short, an SSE is best viewed as a necessary, but not sufficient, condition for sustainability.

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Notes

1. There is still the danger, however, that the supply of nonrenewable resources could run out before they are replaced by renewable substitutes (i.e., if X is too low).
2. Although the methods of EFA proposed by Haberl (2001) make provision for tracking energy stocks within the economy, I would argue that the energy consumption measure that is most relevant to an SSE is energy that is actually used. Therefore, I make a simplification and equate DEC to the energy that is degraded in quality and lost from the economic system. (From an accounting perspective, however, stock changes must still be included to close the energy balance.)
3. Including unused flows is problematic, in part, because of the difficulty in establishing an unequivocal system boundary between the ecosystem and society. There are large uncertainties associated with unused flows, and as one reviewer of this article pointed out, including them in the accounting system could result in substantial distortions.

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