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The resource occupancy to capacity ratio indicator—A common unit to measure sustainability

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A B S T R A C T

Measuring consumption may not be the best method of determining whether society is progressing toward sustainability. We have been developing an indicator, the resource occupancy to capacity ratio (ROC ratio), that uses the concept of "resource occupancy" of important multidimensional aspects related to sustainability such as materials, land use, pollution, and labor. Resource occupancy is defined as the product of an amount of potentially reversible use of something such as a piece of land or material and a period of time of use. The ROC ratio is the ratio of resource occupancy of a material or other resource for a specified time period relative to the total capacity of that material or resource to provide a product or service. The ROC ratio of each aspect is expressed in a common unit (years), thereby improving our ability to compare tradeoffs between the different aspects of sustainability and to evaluate the various alternatives used to develop a sustainable society. Two example alternatives are explored as case studies in a comparison of the ROC ratio and monetary value analyses. The ROC ratio offers a different interpretation of the effects of the two alternatives on each aspect, allowing a new perspective on the effectiveness and costs of alternatives used to foster sustainable development.

1. Introduction

Mass production and mass consumption threaten the sustainability of human society and ecological systems. Although it will not be easy to achieve economic growth and environmental sustainability simultaneously, it is a problem that must be overcome. Generally, environmental efficiency indicators, which compare added value (e.g., GDP, gross domestic product) with resource consumption and the resulting environmental load, have been measured and potential societal improvements have been evaluated by using such indicators. However, can we judge whether society is progressing toward sustainability by measuring consumption? One common method used to evaluate environmental impact is life cycle assessment (LCA), which measures the consumption of natural resources and the accompanying emissions of environmental pollutants (ISO, 2006; Reap et al., 2008a,b). Additional interpretation of LCA results is required, however, to evaluate sustainability (Blengini and Carlo, 2010; Guinee et al., 2011). The ecological footprint (Rees, 1992) provides an easily understandable indicator that compares demands with the planet's capacities, but the scope is limited to fossil fuel consumption (leading to greenhouse gas emissions), land use, food production, biological material production, and other factors that can be converted to a land area of the ecological system. Depletion of mineral resources, for example, is not included. A more comprehensive principle of sustainable development was given by Daly (1990), who refers to the sustainable rate of use of renewable and non-renewable resources (which should be lower than the rate of creation of renewable substitutes) and the emission of wastes, but this is a description of an ideal condition in the future and does not indicate how to lead society in that direction. Alternatives to enhance sustainability may have positive impacts in some regards, but negative impacts in others. During the transition to an ideal sustainable society, we need to select the best alternatives in consideration of the tradeoffs involved. Therefore, a comprehensive indicator is required that is both easy to use and practical.

The difficulties involved in judging the impacts of different alternatives on various aspects of sustainability in a comprehensive manner have been mentioned frequently in the literature (e.g.,

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Robertson et al., 2008). Market price can theoretically mirror various pros and cons of the measures, but because of market failures it does not always reflect future sustainability (Jaffe et al., 2005). These failures have resulted in problems such as global warming and economic disparities between nations. Integrated impact assessment methods with single indexes have been developed (Goedkoop and Spriensma, 2000; Itsubo et al., 2004; Steen, 1999), and their use has enabled comparison of the pros and cons in different aspects of problems. However, these methods do not directly relate to the evaluation of sustainability. In terms of individual aspects, various indicators of sustainable development have been employed on the national and global scales (Dilly and Hüttl, 2009; Eurostat, 2007; OECD, 2000; UNDG, 2003), but only a few indicators directly measure sustainability (Tasaki et al., 2010). The purpose of our study was to create an indicator that more directly measures the effect of alternatives on sustainability.

In this paper, we propose a comprehensive indicator that we have been developing (Fujii et al., 2010) and apply it to two typical alternatives proposed to foster a low carbon society, namely plastics recycling and the substitution of metal with wood (i.e., from a non-renewable resource to a renewable one). The indicator does not measure consumption; rather, it measures "resource occupancy" for a period of time. Resource occupancy, as it is defined here, is different from the concept of consumption, which often implies a momentary and irreversible use of energy, food, and materials. Resource occupancy is defined as the potentially reversible use of some type of resource (e.g., acres of land, tons of material) that can be reused for a subsequent purpose within a specific period of time. Even if we reduce the consumption (combustion) of fossil fuels, their use is irreversible and is eventually not sustainable. More importantly, in an analysis of sustainability, it is important to evaluate ways of effectively using finite but reusable resources, and our indicator focuses on this point. Land development can lead to the disruption of ecosystems, which will need a long time to recover, and sometimes the recovery of a useful material from end-of-life products is economically not feasible. In these cases, the value of resource occupancy is higher because of the long recovery period or lack of reuse of the resource.

Resource occupancy also includes non-material items such as the capacity for water supply or ability of pollutant removal. As a first step, we consider four important items related to sustainability: (1) materials having a finite supply (e.g., base metals and rare metals); (2) land, which is used in the evaluation rather than directly evaluating ecological preservation (Butchart et al., 2010); (3) pollution, where the amount or rate of depuration or sequestration of pollutants by nature is considered; and (4) labor, which is important not only in terms of employment but to evaluate whether alternatives to improve sustainability impose an inordinate burden on laborers. The resource occupancy of these four aspects is compared with the total capacity of each aspect at a specified scale, such as an individual, a region, a country, and the Earth. The indicator can be used to examine various products or functions such as dwellings, clothing, or transportation by measuring the quantity of resource occupancy needed to produce and maintain these functions.

2. Materials and methods

2.1. Overview of the indicator

Consumption is sometimes an ambiguous concept. Regarding the use of iron and the burning of fossil fuels as consumption in the same way prevents an accurate evaluation of the effects in terms of sustainability. Each should be measured by using an appropriate gauge. For example, to measure the effect of the use of iron, both the amount of iron and the period of use are critically important. Resource occupancy, as we define it, is a suitable measurement unit because it includes both the amount and the period of use. Use of the resource occupancy will help us better understand the effects of the use of iron on sustainability.

The resource occupancy to capacity ratio (ROC ratio) is the ratio of resource occupancy to total capacity to yield a product or service (Eq. (1)):

$$\mathrm{ROC} = \frac{OA \times OT}{TA}, \tag{1}$$

where ROC represents resource occupancy to capacity ratio (years), OA is the amount of resource occupancy (kg, km^2, or person, depending on the aspect), OT is period of resource occupancy (years), TA is total capacity (kg, km^2, or person, depending on the aspect). Total capacity is the sum of stock in a society and recoverable reserves in the case of materials, the area of anthropogenic land use in the case of land, and total labor force in the case of labor.

For example, in the case of a rare metal contained in an electronic device, the resource occupancy of the rare metal is the product of the amount of metal contained in the device and the period of use from mining to recycling after use of the electronic device. The ROC ratio is the common indicator used to evaluate the different aspects of sustainability by using a single unit; smaller ROC ratios indicate greater sustainability (Fig. 1).

Because metals do not disappear and can be recycled after so-called consumption, resource occupancy is an appropriate unit to describe their use in terms of sustainable use of a material. In this case, total capacity is the amount of an economically available metal on earth. Conversely, among materials, freshwater is renewable but is consumed in production activities through evaporation and effluent processes. In addition, in terms of total capacity, the rate of freshwater supply (precipitation) is more important than the total abundance of freshwater in evaluating the sustainable use of freshwater. Similarly, as a total capacity, the rate of neutralization or isolation of pollutants in the environment, which is said to be the emission cap of humans to keep the concentration of a pollutant in the environment less than a certain threshold, is more important than the cumulative amount of pollutants removed. In these cases, the resource occupancy as a ratio of the amount to the total speed of supply or removal is appropriate as an indicator:

$$\mathrm{ROC} = \frac{CA}{TS}, \tag{2}$$

where CA represents the amount of consumption of freshwater or emission of pollutants (kg) and TS is the total rate of supply or removal (kg/year).

Although Eqs. (1) and (2) are different, they both represent the resource occupancy to capacity ratio and have a common unit (years).

Because precipitation rates vary from one region to another, it is best to compare consumption of freshwater with the rate of supply in a given area. Similarly, emissions of pollutants that will cause local environmental pollution (e.g. SO_x and NO_x) are better compared with local rates of neutralization or isolation.

Fossil resources are transformed irreversibly by combustion, and their supply is finite. Therefore, current consumption of fossil resources means that we have to acquire energy or materials by means of renewable resources to make up for the lack of fossil resources in the future. However, renewable resources tend to require large areas because of the low density of solar energy. Therefore, combustion of fossil resources is measured as the resource occupancy of land for a certain period (in the future) to produce an equivalent amount of energy.

Thus, by standardizing resource occupancy with total capacity (at various scales) and converting the results into a common unit,