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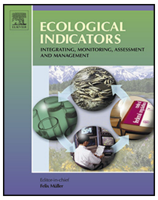

Sinks as limited resources? A new indicator for evaluating anthropogenic material flows

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ABSTRACT

Besides recyclables, the use of materials inevitably yields non-recyclable materials such as emissions and wastes for disposal. These flows must be directed to sinks in a way that no adverse effects arise for humans and the environment. The objective of this paper is to present a new indicator for the assessment of substance flows to sinks on a regional scale. The indicator quantifies the environmentally acceptable mass share of a substance in actual waste and emission flows, ranging from 0% as worst case to 100% as best case. This paper consists of three parts: first, the indicator is defined. Second, a methodology to determine the indicator score is presented, including (i) substance flows analysis and (ii) a distant-to-target approach based on an adaptation of the Ecological Scarcity Method 2006. Third, the metric developed is applied in three case studies including copper (Cu) and lead (Pb) in the city of Vienna, and perfluorooctane sulfonate (PFOS) in Switzerland. The following results were obtained: in Vienna, 99% of Cu flows to geogenic and anthropogenic sinks are acceptable when evaluated by the distant-to-target approach. However, the 0.7% of Cu entering urban soils and the 0.3% entering receiving waters are beyond the acceptable level. In the case of Pb, 92% of all flows into sinks prove to be acceptable, and 8% are disposed of in local landfills with limited capacity. For PFOS, 96% of all flows into sinks are acceptable. 4% cannot be evaluated due to a lack of normative criteria, despite posing a risk for human health and the environment. The examples demonstrate the need (i) for appropriate data of good quality to calculate the sink indicator and (ii) for standards, needed for the assessment of substance flows to urban soils and receiving waters. This study corroborates that the new indicator is well suited as a base for decisions regarding the control of hazardous substances in waste and environmental management.

1. Introduction

"I do not worry about peak oil whatsoever. We have plenty of oil, gas, and coal to last for hundreds of years, and we are not running out. But we are running out of room in the atmosphere to store our exhaust." Schnoor (2013) highlights the sink "atmosphere" as constraint for anthropogenic carbon before the sources run dry. The overriding question is if we are running out of "room in sinks" for other substances, too. Annually, millions of tons of materials are exploited from the earth crust or are produced synthetically, and processed into consumer and investment goods. After years or decades in use, the materials are discarded and meet their fate in terms of recycling or disposal in sinks. Therefore, geogenic sinks are available to a certain extent and anthropogenic sinks have to be provided where geogenic sinks are lacking. Geogenic sinks are part of biogeochemical cycles (e.g. Abeles et al., 1971; Berg and Dise, 2004; Feichter, 2008; Fong and Zedler, 2000; ICSU, 1989; Molina and Rowland, 1974; Paterson et al., 1996; Yanai et al., 2013). Anthropogenic sinks are manmade and refer to technologies such as incinerators, sanitary landfills, and sewage treatment plants (e.g. Brunner, 1999; Brunner and Tjell, 2012; ISWA, 2013; Morf and Brunner, 2005; Vogg, 2004; Zeschmar-Lahl, 2004). In general, materials must be directed to sinks in a way that no adverse effects arise for humans and the environment (Tarr, 1996).

To avoid unacceptable overloads, several authors have suggested metrics that focus on the relation between anthropogenic off-flows and potential impacts (Table 1). In common, these metrics (i) operate on a substance specific level, (ii) focus on human activities within regions, and (iii) work with a set of indicators. To calculate the indicator, a combination of descriptive and normative assessment methods is needed:

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Table 1
Selected studies applying pressure, proxy and impact oriented indicators characterizing environmental sustainability.

Reference	Spatial level	Pressure indicators[a]	Proxy indicators[b]	Impact indicators[c]
Alfsen and Sæbø (1993)	Norway		X	
Gilbert and Feenstra (1994)	Netherlands		X	
Nilsson and Bergström (1995)	Sewage Treatment Plant	X		
Azar et al. (1996)	World	X	X	
UNCSD (1996)	Not specified	X	X	X
Van der Voet (1996)	European Union	X	X	
Guinée et al. (1999)	Netherlands	X	X	X
Umweltbundesamt (1999)	Austria	X	X	
UNCHS (2001)	World	X		
Graymore et al. (2010)	World	X	X	
EEA (2012)	European Union	X	X	X

[a] Examples for pressure indicators are the amount of waste and emission flows.

[b] Examples for proxy indicators are (i) the spatial and temporal range of substances (Scheringer and Berg, 1994), (ii) the persistence, bio-accumulation, and toxicity of substances (European Parliament, 2006), (iii) legal limits or political agreements (Frischknecht et al., 2009), (iv) the ratio of anthropogenic to geogenic substance flows (Förstner and Müller, 1973; Reimann and de Caritat, 2005), and (v) exposure assessments (U.S. EPA, 2011).

[c] Examples for impact indicators are the number of human deaths due to certain substance flows into geogenic sinks.

- Descriptive methods analyze the fate and behavior of substances through the anthroposphere and the environment. For this purpose, the tools substance flow analysis (SFA) and environmental fate modeling (EFM) have been developed (e.g. Brunner and Rechberger, 2004; Mackay et al., 2006; OECD, 2007; UNEP, 2002). To calculate *pressure indicators*, researchers devoted much effort to quantify substance flows from human activities into geogenic and anthropogenic sinks (e.g. Buser and Morf, 2009; Chen and Graedel, 2012; Henseler et al., 1992; Ott and Rechberger, 2012).
- Normative methods focus on the cause-effect chain of substances. Depending on the available knowledge, they either refer to "known damage due to known causalities", or "known damages due to unknown causalities", or "unknown damage due to unknown causalities" (adopted from Hofstetter, 1998). If damage and causalities are known, *impact indicators* can be provided. Therefore the tools risk assessment (RA) and life cycle impact assessment (LCIA) have been developed. LCIA focuses on the assessment of emissions along the whole life cycle chain of products and services rather than on emissions from entire human activities within regions (Loiseau et al., 2012). In general, LCIA methods rely on the scientific treatment of cause-effect relations from the intervention level toward the impact level. The LCIA method "Ecological Scarcity 2006" is an exception, because it considers the definition of critical flows into sinks based on legal limits and political agreements (Jungbluth et al., 2012). However, for the majority of substances placed on the market, the damages and causalities are partly or totally unknown (Berg and Scheringer, 1994; Grandjean, 2013). In this case, *proxy indicators* with more or less predictive power are used to approximate potential impacts.

Summarizing, the indicators developed so far focus on certain levels along the cause-effect chain. This includes the intervention level (*pressure indicators*), the effect level (*impact indicators*) or a level between intervention and effect (*proxy indicators* toward impacts). To our knowledge, individual indicators have not been linked yet systematically in view of ecological and human health assessment of regions. At present, the question "Which amounts of waste and emission flows are acceptable and unacceptable, respectively?" cannot be answered with a single indicator. To overcome this gap, Döberl and Brunner (2004) proposed to amend the tool box of sustainability metrics by the following indicator:

$$\frac{\text{Amount of substances a region or process directs into appropriate final sinks}}{\text{Total amount of substances emitted by a region or process}} \quad (1)$$

Beyond the definition of the indicator, there is no operationalization in terms of assessment methods presented. However, the denominator of Eq. (1) refers to the intervention level and the numerator of Eq. (1) refers to a final level along the life cycle chain.

The present paper is inspired by Eq. (1), and advances it further to make it operational for application. The aim of the paper is to develop an assessment method that

- is able to consider specific substances,
- takes into account discarded material flows (wastes, emissions, substance flows from wear, corrosion, and weathering) from human activities within a spatial unit,
- covers geogenic and anthropogenic sinks for discarded material flows,
- allows the integration of normative criteria such as *proxy* and *impact criteria*,
- consists of a quantifiable indicator.

To achieve this goal, we relate acceptable to actual substance flows into sinks. Actual flows are determined by regional SFA, usually on an annual base. Acceptable flows can be determined by any environmental assessment method. We have chosen a distant-to-target approach according to the Ecological Scarcity (ES) method, and apply this framework in three case studies. The indicator score is determined for (1) copper (Cu) in the city of Vienna, (2) lead (Pb) in the city of Vienna, and (3) perfluorooctanesulfonate (PFOS) in Switzerland. Based on the findings, we present options to control the indicator score. The resulting indicator serves as a guide to identify potential constraints for sinks to accommodate waste and emission flows. The indicator is intended to support material management in view of potential sink limitation. Accordingly, we propose to add this indicator to existing metrics for characterizing the environmental dimension of sustainability.

2. Material and methods

In the following sections, we (i) define the indicator, (ii) present the methods for calculating the indicator score, and (iii) apply the metric in three case studies.

2.1. Indicator definition

The sink indicator (λ) quantifies the environmentally acceptable mass share of a substance in actual waste and emission flows.