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A conceptual framework for selecting environmental indicator sets

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ABSTRACT

In recent years, environmental indicators have become a vital component of environmental impact assessments and "state of the environment" reporting. This has increased the influence of environmental indicators on environmental management and policy making at all scales of decision making. However, the scientific basis of the selection process of the indicators used in environmental reporting can be significantly improved. In many studies no formal selection criteria are mentioned and when selection criteria are used they are typically applied to indicators individually. Often, no formal criteria are applied regarding an indicator's analytical utility within the total constellation of a selected set of indicators. As a result, the indicator selection process is subject to more or less arbitrary decisions, and reports dealing with a similar subject matter or similar geographical entities may use widely different indicators and consequently paint different pictures of the environment. In this paper, a conceptual framework for environmental indicator selection is proposed that puts the indicator set at the heart of the selection process and not the individual indicators. To achieve this objective, the framework applies the concept of the causal network that focuses on the inter-relation of indicators. The concept of causal networks can facilitate the identification of the most relevant indicators for a specific domain, problem and location, leading to an indicator set that is at once transparent, efficient and powerful in its ability to assess the state of the environment.

1. Introduction

National and international environmental regulations are rapidly increasing in number, which has lead to a boom in environmental assessment reports (EEA, 1999; McRae et al., 2000; Wascher, 2000; World Resources Institute, 2000; EEA, 2001; OECD, 2001; The Heinz Center, 2002; UNEP, 2002; EPA, 2003; EEA, 2005b; Esty et al., 2005; World Resources Institute, 2005). Environmental assessments have become commonplace in planning and evaluation at all scales of decision making, from private enterprises to town councils, governments and international forums. Environmental indicators, as prime assessors of the pressures on the environment, of the evolving state of the environment, and of the appropriateness of policy measures, have come to play a vital role in environmental reporting.

Environmental indicators have taken on such importance because they provide "a sign or signal that relays a complex message, potentially from numerous sources, in a simplified and useful manner" (Jackson et al., 2000, p. vii). Environmental indicators provide an important source of information for policy makers and help to guide decision-making as well as

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monitoring and evaluation (OECD, 1999), because they can provide valuable information on complex issues in a relatively accessible way. However, it is a major challenge to determine "which of the numerous measures of ecological systems characterize the entire system yet are simple enough to be effectively and efficiently monitored and modeled" (Dale and Beyeler, 2001, p. 4).

In an earlier paper (Niemeijer, 2002), data-driven and theory-driven approaches to the development of environmental indicator sets were examined. In the process of writing that paper, it was realized that while indicator reports and their use of indicators is undeniably useful, there is still considerable room for improvement in the indicator selection process. As Dale and Beyeler (2001, p. 6) observe, "lack of robust procedures for selecting indicators makes it difficult to validate the information provided by those indicators." A more rigorous and transparent indicator selection process will increase both the value and the scientific credibility of environmental assessment reports and ensure they meet management concerns (Belnap, 1998; Slocombe, 1998; Dale and Beyeler, 2001). Another benefit of a more structured indicator selection process is that it allows for proper conceptual validation of indicators (Bockstaller and Girardin, 2003). It may also help in identifying indicators that can link ecological dimensions with environmental, social and economic dimensions, which is vital for good policy making (Niemi and McDonald, 2004).

While a number of conceptual frameworks are used within the context of environmental assessments (for example EPA (1998) ecological risk assessment framework), the most common frameworks used in indicator based studies are the driving force–pressure–state–impact–response (DPSIR), pressure–state–response (PSR), or driving force–state–response (DSR) conceptual frameworks, which organize and structure indicators in the context of a so-called causal chain (e.g., Hammond et al., 1995; OECD, 1998, 1999; Smeets and Weterings, 1999; EEA, 2000; Wascher, 2000; Bridges et al., 2001; OECD, 2001). In the causal chain, social and economic developments are considered driving forces that exert pressure on the environment, leading to changes in the state of the environment. In turn, these changes lead to impacts on human health, ecological systems and materials that may elicit a societal response that feeds back on the driving forces, pressures, or on the state or impacts directly (Smeets and Weterings, 1999, p. 6).

In this paper it is argued that these causal chain frameworks should be used to frame the indicator selection process. In current practice, indicators are often selected either based on historical practices and regulations or based on "intuitive assessment of experts" (Bossel, 2001, p. 2) and on the degree to which they meet a number of criteria individually (e.g., NRC, 2000; OECD, 2001; EEA, 2005a), rather than on the basis of how they jointly provide an answer to our environmental questions. As Swart et al. (1995) argue, it is important to distinguish between criteria that apply to indicators as a set, and those that apply to individual indicators. Conceptual indicator frameworks can potentially play an important role in the indicator selection process and in developing consistent indicator sets. This is especially true in situations where the whole range from driving forces and pressures to environmental impacts needs to be covered.

In this paper an enhanced DPSIR framework (eDPSIR in brief) is used that does not consider individual causal chains but, inspired by systems thinking (Odum, 1953), tackles the complexities of the real world by looking at causal networks in which multiple causal chains interact and inter-connect (Niemeijer and de Groot, 2007). The concept of causal networks in itself is not new. Causal networks have been used in mathematics (Perl, 2001) and, referred to as causal webs, also in the fields of health and environmental health (e.g., Kay et al., 2000). The idea of applying a systems approach to indicator selection is not new either (e.g., Bossel, 2001). What is novel in the approach taken here is the integration of familiar concepts, such as the systems approach, causal networks and the DPSIR framework in a systematic indicator selection procedure that makes the inter-relation of indicators an explicit part of the indicator selection process. The need for such a systematic, transparent and generally applicable indicator selection procedure was again underlined as a key finding in a recent report from the US National Commission on Science for Sustainable Forestry (NCSSF, 2005, p. 28) that stated:

> "The bottleneck in effective selection and use of indicators is not a lack of good indicators or good science, but rather the lack of [...] a clear process for selecting indicators [...] The reliability of identified measures is frequently questioned, at least in part because selection of indicators often has lacked transparency, social inclusiveness, and/or a logical structured process of selecting indicators."

This paper consists of two parts. The first part begins with a brief introduction of the concept of environmental indicators and causal-chain frameworks. It then moves to a discussion of indicator selection and its impact on indicator reporting. The second part introduces the enhanced DPSIR framework and, using a concrete example, illustrates how this so-called eDPSIR framework can lead to better and more transparent indicator selection.

2. Environmental indicators and their selection

2.1. *Environmental indicators and the causal-chain frameworks*

Hammond et al. (1995, p. 1) describe an indicator as "something that provides a clue to a matter of larger significance or makes perceptible a trend or phenomenon that is not immediately detectable. [...] Thus an indicator's significance extends beyond what is actually measured to a larger phenomena of interest". To give an example, measuring body temperature not only gives the current temperature of the human body, but if that temperature is higher than normal also provides a strong indication that the person is ill and currently experiencing a virus or infection. So body temperature is not just a temperature indicator, but also a human health indicator.

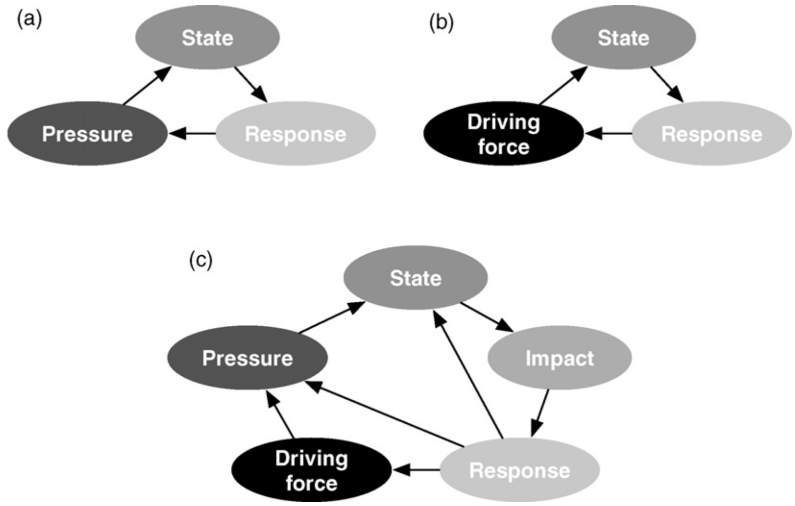

Fig. 1 – The (a) PSR, (b) DSR, and (c) DPSIR frameworks.

Just like human body temperature is a human health indicator, environmental indicators provide insight in the condition of the environment. Environmental indicators typically include physical, biological and chemical indicators (Smeets and Weterings, 1999) and generally comprise indicators of environmental pressures, conditions and (societal) responses (OECD, 1993). The latter categorization is used in the three causal chain frameworks (shown in Fig. 1), pressure–state–response (PSR), driving force–state–response (DSR), and driving force–pressure–state–impact–response (DPSIR), which have a lot in common. In each framework a causal chain is recognized whereby a distinction is made between (1) forces that act on the environment, (2) changes that, as a consequence, take place in the environment and (3) the societal reaction to those changes. Where the frameworks mainly differ is in the degree in which they subdivide the steps in the causal chain.

The first framework, the pressure–state–response (PSR) framework (Fig. 1a) divides indicators in pressure, state and response indicators through the following logic: "pressure on the environment from human and economic activities, lead to changes in the state or environmental conditions that prevail as a result of that pressure, and may provoke responses by society to change the pressures and state of the environment" (OECD, 1999, p. 12).

The second framework is the driving force–state–response (DSR) framework (Fig. 1b). In this framework the "pressure" component is replaced with the concept of "driving forces". This concept, in the words of OECD (1999, p. 14), "recognises that agricultural activities can both produce beneficial impacts to enhance environmental quality [...] and also have harmful impacts on the environment." The concept of driving forces also accommodates "a broader coverage of the influences affecting the environment in agriculture and sustainable agriculture, including farmer behaviour, government policies, economic, social, and cultural factors" (OECD, 1999, p. 14).

The third framework, the driving force–pressure–state–impact–response (DPSIR) framework (Fig. 1c) follows essentially the same general pattern as the other two frameworks but distinguishes more steps along the way. It distinguishes between indirect driving forces such as social and economic developments and pressures such as emissions that directly influence the environment. It further distinguishes between the state of the environment (for example concentrations of pollutants) and the impacts of (changes in) the environmental state on human health, ecological systems and materials (Smeets and Weterings, 1999, p. 6).

So while there are some differences between these frameworks in terms of terminology and the degree of detail, they are all based on the causal chain concept.

2.2. *Current indicator selection practice*

The causal chain frameworks discussed in the previous section help structure our thinking about indicators in terms of causality chains of cause and effect. However, indicator-based environmental reports such as EEA (1999), OECD (1998), Wascher (2000) typically make use of these frameworks only for presenting indicators, not as a formal part of the indicator selection process. Instead, indicators are primarily selected on the basis of individually applied criteria, not on how they are inter-related through causality.

Here are some examples. Schomaker (1997) suggests that indicators should be SMART: specific, measurable, achievable, relevant and time-bound. This implies that an indicator should be clearly and unambiguously defined, be measurable in qualitative or quantitative terms, be achievable in terms of the available resources, be relevant for the issue at hand and be sensitive to changes within policy time-frames. OECD (2001, p. 203) offers just three selection criteria: policy relevance, analytical soundness and measurability. One of the most extensive lists of criteria is offered by NRC (2000, pp. 52–59), which provides the following evaluation criteria: general importance, conceptual basis, reliability, temporal and spatial scales of applicability, statistical properties, data requirements, necessary skills, robustness, international compatibility, and finally, costs, benefits and cost-effectiveness. In other words, an indicator should bear on a fundamental process or widespread change, have a strong scientific basis, have a proven track record, provide information at the right spatial scales and within appropriate time-frames, have excellent statistical properties that allow unambiguous interpretation, have manageable data requirements, not require excessive data collection skills, be relatively insensitive to expected sources of interference, be compatible with indicators developed and used in other regions, and, finally, the benefits of the information provided by the indicator should outweigh the costs of usage.

Riley (2000) suggests that indicators should ideally have the following properties: universality (applicable to many areas/situations and scales of measurement), portability (repeatability and reproducibility), sensitivity to change, operationally simple, inexpensive, already existing with historical comparative data, and have wide (international) use. Dale and Beyeler (2001), focusing on ecological indicators, suggest that these should be easily measured, be sensitive to stresses on the system, respond to those stresses in a predictable manner, be anticipatory (signify an impeding change), predict changes that can be averted by management, be integrative (the full suit of indicators should cover the key ecological gradients), should have known responses to disturbances, stresses and changes over time, and have low variability in response. CBD (1999), looking at biodiversity indicators, suggests that indicators should: quantify information so that its significance is apparent, be user-driven to be relevant for the target audience, be scientifically credible, be responsive to changes in time and/or space, be simple and easily understood by the target audience, be based on information that can be collected within realistic capacity and time limits, and be linkable to socio-economic developments and indicators of sustainable use and response. Pannell and Glenn (2000), talking about sustainability indicators for agriculture, note that it is desirable that there is a high uncertainty about the level of the indicator to be monitored, a low uncertainty about links between the indicator, management practices and production (in other words if the indicator has taken on an undesirable level the insight necessary to ‘‘fix’’ the problem is present), that the indicator can be measured reliably and accurately, and that the cost of monitoring the indicator at the necessary scale are low.

Kurtz et al. (2001) take a slightly different approach than most of the other studies by focusing on hierarchical evaluation guidelines for indicators instead of selection criteria. The idea is that unlike criteria, the guidelines provide a framework to ask the right questions in a structured manner without by themselves determining indicator applicability or effectiveness. They recognize four phases, leading from conceptual relevance to feasibility of implementation to response variability and finally to interpretation and utility. Each phase is composed of 2–5 guidelines leading to a total of 15 guidelines. These are: relevance to the assessment, relevance to the ecological resource or function at risk, feasibility of data collection methods, feasibility of the logistics, feasibility of the information management, feasibility of the quality assurance, feasibility of the monetary costs, estimation of measurement error, within-season temporal variability, across-year variability, spatial variability, discriminatory ability, data quality objectives, assessment thresholds (for when to take action), and finally, linkage to management actions.

Finally, EEA (2005a) gives nine criteria for their core set of indicators of which four are policy related: Policy relevance, progress towards policy targets, understandability of the indicator, and part of EU priority policy issues. Four criteria are data related: availability of routinely collected data, spatial coverage of data, temporal coverage of data, and national scale and representativeness of data (allowing benchmarking). The last criterion is science-focussed, namely whether an indicator is methodologically well founded. The EEA clearly has a strong focus on practical and policy dimensions.

Table 1 presents an overview of the indicator selection criteria taken from the discussed sources. Similar criteria where grouped together under a single criterion to maintain some overview. In some cases multiple criteria as mentioned by one source were grouped together in the table because they all involved different aspects of the same basic issue. For example, the guidelines listed under the ‘‘response variability’’ phase of Kurtz et al. (2001) are all in one way or another related to the criterion of ‘‘statistical properties’’ and thus jointly added as a single count in that row of Table 1. As a consequence, the table provides an overview and does not cover all the nuances of the original publications.

Even though the list in Table 1 is quite extensive with 34 criteria, it is remarkable that only 3 of the listed selection criteria pertain to the inter-relation of indicators: ‘‘integrative’’, ‘‘linkable to societal dimension’’ and ‘‘links with management’’. What is more, each of these is only mentioned by at most three of the eight publications. The most common criteria are measurability, low resource demand, analytical soundness, policy relevance and sensitivity to changes within policy time frames. Generally speaking, one can say that there are differences in emphasis and detail between the different studies, but the focus is generally on criteria for individual indicators, not on criteria that relate indicators to one another. There are some exceptions, for example, Swart et al. (1995) mention three set-level criteria: (1) balanced coverage of the population, economic, environmental and ecological subsystems; (2) cover pressure, state, impacts and responses; (3) be capable of measuring progress towards policy goals. However, while these criteria will help to ‘‘balance’’ an indicator set, they do not provide much of a handle to structure the selection process itself.

The consequence of the tendency to focus on individual indicators is that environmental reports typically provide information on the criteria they used to select individual indicators but not on why a particular constellation of indicators was chosen or why certain other indicators were considered irrelevant. Let us take an example. Two recent environmental indicator studies by international bodies, one by the Organization for Economic Co-operation and Development or OECD (2001) and one by the European Environment Agency or EEA (2000), looked at the problem of ozone depletion. The OECD study selected indicators on the basis of policy relevance, analytical soundness and measurability. The EEA study selected indicators primarily on the basis of policy relevance and on the basis of data availability. There is clearly quite some overlap in criteria. Both studies mention policy relevance, while measurability and data availability typically coincide as both studies present currently available data sets. Only the OECD study mentions analytical soundness, but it is unlikely that this criterion

Table 1 – Common environmental indicator selection criteria

Criterion	Count	Description/explanation
Scientific dimension		
Analytically soundness	4	Strong scientific and conceptual basis
Credible	1	Scientifically credible
Integrative	1	The full suit of indicators should cover key aspects/components/gradients
General importance	1	Bear on a fundamental process or widespread change
Historic dimension		
Historical record	2	Existing historical record of comparative data
Reliability	2	Proven track record
Systemic dimension		
Anticipatory	1	Signify an impending change in key characteristics of the system
Predictable	1	Respond in a predictable manner to changes and stresses
Robustness	1	Be relatively insensitive to expected source of interference
Sensitive to stresses	1	Sensitive to stresses on the system
Space-bound	1	Sensitive to changes in space
Time-bound	4	Sensitive to changes within policy time frames
Uncertainty about level	1	High uncertainty about the level of the indicator means we can really gain something from studying it
Intrinsic dimension		
Measurability	4	Measurable in qualitative or quantitative terms
Portability	1	Be repeatable and reproducible in different contexts
Specificity	1	Clearly and unambiguously defined
Statistical properties	3	Have excellent statistical properties that allow unambiguous interpretation
Universality	1	Applicable to many areas, situations, and scales
Financial and practical dimensions		
Costs, benefits and cost-effectiveness	1	Benefits of the information provided by the indicator should outweigh the costs of usage
Data requirements and availability	3	Manageable data requirements (collection) or good availability of existing data
Necessary skills	1	Not require excessive data collection skills
Operationally simplicity	2	Simple to measure, manage and analyse
Resource demand	5	Achievable in terms of the available resources
Time demand	1	Achievable in the available time
Policy and management dimensions		
Comprehensible	2	Simply and easily understood by target audience
International compatibility	2	Be compatible with indicators developed and used in other regions
Linkable to societal dimension	1	Linkable to socio-economic developments and societal indicators
Links with management	3	Well established links with specific management practise or interventions
Progress towards targets	1	Links to quantitative or qualitative targets set in policy documents
Quantified	1	Information should be quantified in such a way that it significance is apparent
Relevance	4	Relevance for the issue and target audience at hand
Spatial and temporal scales of applicability	2	Provide information at the right spatial and temporal scales
Thresholds	1	Thresholds that can be used to determine when to take action
User-driven	1	User-driven to be relevant to target-audience

Source: Based on Schomaker (1997), OECD (2001), NRC (2000), Riley (2000), Dale and Beyeler (2001), CBD (1999), Pannell and Glenn (2000), Kurtz et al. (2001), and EEA (2005a).

played no role in the EEA selection procedure, even though it is not explicitly mentioned. So the criteria are quite similar, but as can be seen in Table 2, there is quite a difference between the two studies in terms of the selected indicators. Even where both studies measure the same attribute (for example UV radiation), they use a different measure (i.e., the OECD uses ground level UV-B radiation versus increase in UV radiation used by the EEA). In other cases the differences between the indicators are even larger and even an approximate match is not possible. Not in a single case was the same indicator used.

The big question is of course why these indicator sets for ozone depletion differ so much? Was it differences in data availability? Perhaps, but then again, there are large overlaps in terms of the member countries of the two organizations. One likely factor is that the authors of these reports have started out with a different frame of reference. One noticeable difference is that the OECD study relies on the PSR framework, while the EEA study relies on the DPSIR framework. But, how that would have affected indicator selection is unclear as neither report presents a clearly outlined procedure that leads from criteria and/or framework to indicator set. Probably the authors also had a different perspective on what the crucial factors are and how the different environmental problems inter-relate. Given these differences, they are likely to have followed different conceptual ‘‘frameworks’’ and followed different logical paths to arrive at the indicators that were eventually selected. However, because such considerations

Table 2 – Approximate match between stratospheric ozone depletion indicators used by the OECD and EEA

Position in causal chain	OECD (2001, p. 20)	EEA (2000, p. 53)
Driving force (EEA)/indirect pressure (OECD)	–	Radiative forcing of ozone depleting substances
	Production/consumption of CFCs, halons and other ODS[a]	Production of ozone depleting substances
	Index of apparent consumption of ODS	–
Direct pressure (OECD)	Release of ODS[a]	–
State	Atmospheric ODS concentrations[b]	Total potential chlorine and bromide concentrations in the troposphere
	Stratospheric ozone levels over selected cities	Average ozone column in March
	Ground level UV-B radiation[a]	Increase in UV radiation
Response	Existing CFC recovery rates[a]	–
	–	Contribution to multilateral fund to assist developing countries to implement the Montréal protocol

[a] Suggested, but not actually presented in this OECD (2001) publication.
[b] Suggested in the chapter on ozone layer depletion, but present in the chapter on climate change of OECD (2001).

are undocumented, it is impossible to reconstruct the indicator selection process behind these studies.

Absence of a properly documented indicator selection process is not a minor issue. Which indicators are considered highly influences conclusions as to whether environmental problems are serious or not, whether conditions are improving or degrading, and in which direction causes and solutions need to be sought. It is therefore very important to have a well-defined and transparent procedure leading from problem definition to indicator set to interpretation of the indicator values. This is contrary to current practice, which usually involves expert panels selecting several ''best'' indicators that together make up the indicator set to tackle a specific environmental issue (Bossel, 2001; Bockstaller and Girardin, 2003). In our view, science and analytical soundness are much better served by working on the basis of a concrete framework that guides the selection of indicators through clearly outlined procedures that direct indicator selection on the basis of analytical logic rather than individual characteristics. Ideally, each indicator in an indicator set should have a particular function in the analytical problem solving logic of the environmental issues that are to be addressed with the use of indicators. It is with this idea in mind that we set out to develop an environmental indicator selection framework that focuses on the set of indicators and not just on the individual indicator.

3. Use of the enhanced DPSIR framework for indicator selection

3.1. *An introduction to the causal network concept*

In the previous sections, it was argued that indicator selection tends to be insufficiently grounded within a conceptual framework and therefore overemphasises individual indicator characteristics as formal selection criteria rather than the function of the indicators within an analytical problem solving logic. More than the current casual-chain frameworks, the enhanced DPSIR framework (see Fig. 2 for an example and (Niemeijer and de Groot, 2007) for a more extensive discussion) is well suited to provide conceptual guidance for indicator selection. The enhanced DPSIR framework or eDPSIR for short, is not based on the concept of the causal chain as used by the current causal chain frameworks, but on the concept of a causal network.[2] Causal chain frameworks consider multiple parallel causal chains leading from driving force indicators to pressure indicators, state indicators, impact indicators and finally to response indicators, with each chain covering a specific issue. A causal network based framework includes the inter-relations between the various causal chains. A causal network therefore is able to more effectively capture the whole range of causes and effects and their inter-relations that typically involve a large number of environmental indicators and crosses the boundaries of individual environmental issues.

A causal network is not unlike the flowcharts of the process-based simulation model used in environmental systems analysis. Both are graphical representations of the interconnections between different components and processes. The key difference is that for a causal network the kind of detail that would be required to build a process-based model is not needed, nor do all relationships need to be fully quantified.

With the eDPSIR framework the concept of a causal network is used as a structuring mechanism to select indicators. In our discussion of the use of the concept of a causal network a number of other terms and concepts will be introduced such as ''abstract indicators'', ''pressure interface'', ''key nodes'', ''correction indicators'', and ''indicator functions''. Throughout this part of the paper we will be drawing examples from a very much simplified nitrogen eutrophication problem.

3.2. *Building a causal network*

The first step to working with a causal network is to build one. Below the five main steps for building a causal network are outlined.

[2] Note that we are not referring to the mathematical concept of causal networks (Perl, 2001) though there are clear similarities.

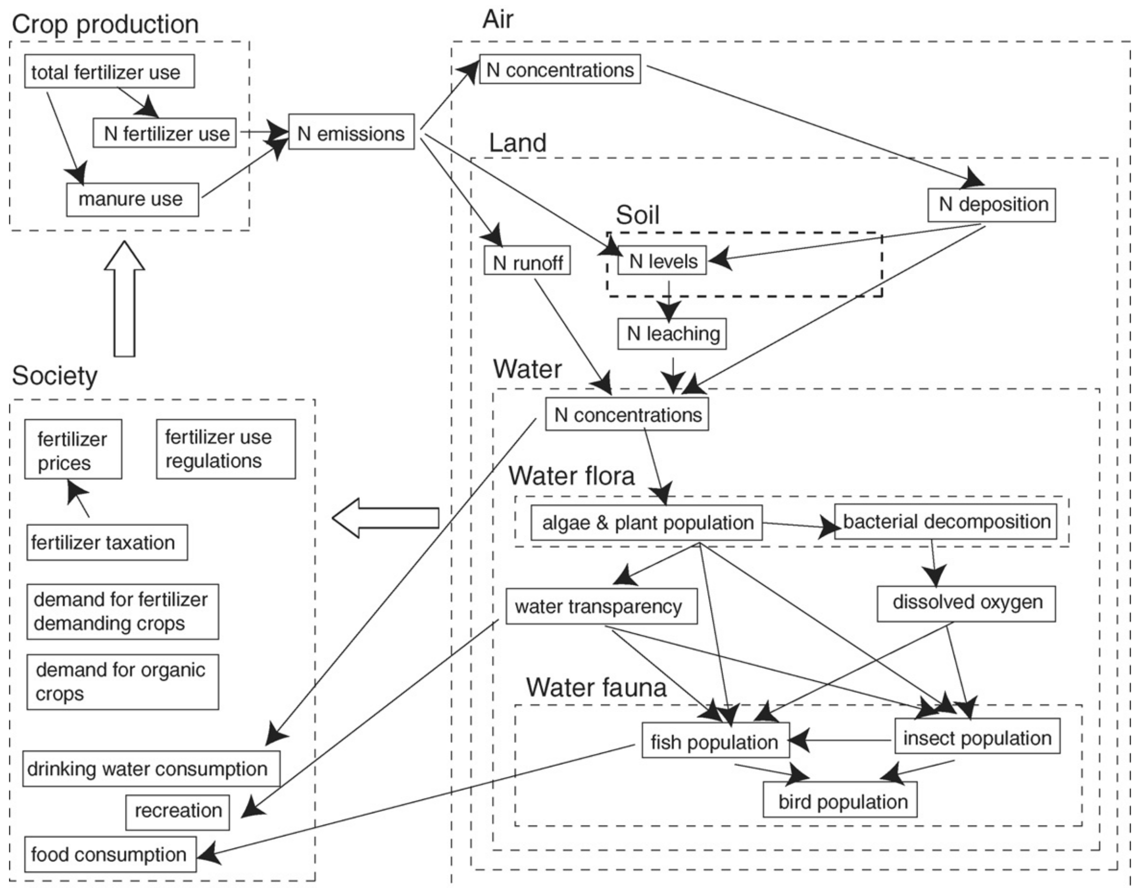

Fig. 2 – A sample causal network for our nitrogen example. Specific links are drawn with thin black arrows, general links with large open arrows. The dotted lines indicate the different environmental and societal compartments.

Steps to build a casual network:

(1) Broadly define the domain of interest.
(2) Determine boundary conditions that can help determine which aspects to cover and which to omit.
(3) Determine the boundaries of the system.
(4) Identify (abstract) indicators covering the factors and processes involved.
(5) Iteratively map the involved indicators in a directional graph:
  (a) Organize indicators in terms of environment related indicators, society related indicators and those at the pressure interface.
  (b) Organize indicators in sub-categories such as economic sectors or environmental compartments
  (c) Draw the causal network with nodes connected with arrowed arcs showing the cause-effect pathways.

- *Step 1. Defining the domain of interest*: First, a particular issue or problem to look at needs to be defined. The domain of interest may be very broad (e.g., the impact of agriculture on the environment), but if a clearly outlined specific issue is already identified, that certainly helps in keeping the causal network small and manageable. In our example, the domain of interest will be defined as the ecological impact of nitrogen fertilization on surface water ecosystems bordering agricultural land.
- *Step 2. Determining boundary conditions*: Boundary conditions, such as whether a specific ecological system, climate, socio-economic context, etc. is concerned, need to be considered. In our example, we will be looking at a temperate climate situation as found in The Netherlands.
- *Step 3. Determining the boundaries of the system*: The boundaries of the system need to be defined. In other words, what will be included and what will be considered just in terms of outputs and inputs. In our example, we want to limit ourselves to the in situ situation and not extend the causal network to processes occurring outside the research area (e.g., manufacturing of fertilizer, nitrogen emissions to the sea).
- *Step 4. Identifying abstract indicators for the main factors and processes*: One may identify concrete indicators or just identify abstract indicators that are useful at a conceptual level but not necessarily concrete enough to actually collect data for. A good example is ‘‘animal population’’. This is an abstract indicator because it does not specify the kind of animal nor the way in which population should be defined and measured (e.g., total population, species composition, average age). Generally speaking, selecting a concrete

indicator is best done after it has been established that this is the factor or component that should actually be measured.

At the stage of indicator identification, it is possible to go into great detail, but it is equally possible to work along broad lines and consider only the most significant indicators, processes and factors. It is even possible to work out certain processes in detailed sub-processes because they seem particularly relevant for the research question at hand and stick to the main processes for other aspects. There are no hard rules here and at any time (during subsequent steps) it is possible to delve deeper or reduce detail. The DPSIR framework can be used to get a handle on all the different components that need to be considered. The best approach is to start out with the pressures, as these are typically more concrete than the driving forces and then subsequently work forward from pressures to state, impact and responses and then backward from pressures to driving forces. At this stage there is no reason to be too much concerned about the category in which an indicator should be placed or to develop an exhaustive list of indicators. This is merely an intermediate step intended to facilitate getting started with mapping the causal network. Table 3 shows such a first selection of abstract indicators for our nitrogen example.

- *Step 5. Iteratively mapping the indicators in a direction graph*: Here we put together the actual causal network. First, the indicators listed in step four are organized into environment related indicators, society related indicators and those at the pressure interface of interest. The term pressure interface refers to the economic sector or human activity that exerts a pressure on the environment. In the case of our example, crop production may be considered the pressure interface where society exerts pressure through its use of nitrogen on the environment. Next, the indicators can be organized in sub-categories. The society related indicators could, for instance, be divided in those related to the role of the state, the commercial sector and the consumers. Environment related indicators might, for instance, be divided into the different environmental compartments: air, soil, water, as will be done for our example. Fig. 2 shows a causal network for our nitrogen example.

The causal network shown in Fig. 2 may be considered a first approximation. Some parts are spelled out in detail, whereas other parts are relatively vague. It is at the next stage, where the causal network for indicator selection is applied, that it will become clear what parts need to be explored in more detail.

3.3. *Using the causal network for indicator selection*

The causal network developed in the previous section can be used as a starting point to answer a variety of research questions. It is with an actual concrete research question that one can really start using the causal network. This research question may be a broad-brush question (e.g., measuring progress towards sustainability of a country) or a very specific question (e.g., the impact of a specific intervention on fresh water quality). The key point is that the better the questions or objectives are defined, the better the indicators can be selected (NCSSF, 2005). This section focuses on how the causal network can be put to use to select indicators for a specific research question. There are again a number of steps to follow:

(1) Define the research question:
   (a) Determine the kind of available information.
   (b) Determine the scale at which to work.
   (c) Determine where in the DPSIR chain the focus lies.
   (d) Determine whether an environment, or human-centred perspective is required.
(2) Identify key-nodes in the causal network and explore relevant sections of the causal network in more detail.
(3) Select the best concrete indicators for the selected nodes.

- *Step 1. Define the research question*: A research question needs to be defined that is as concrete as possible. This is an important step because there are no perfect indicator sets that are relevant for all problems at hand (NCSSF, 2005). The relevance and utility of an indicator is largely determined by the research question(s) that are to be answered and by the combination of indicators that is used (Swart et al., 1995). To answer a generic question, such as finding a good set of agri-environmental indicators to measure sustainability in the agricultural sector, a causal network can be used to find the most generally useful indicators. However, while that set of indicators will be useful to address a wide range of research questions, it will not be as fine-tuned as a set selected just to tackle one very specific environmental question or issue.

There are a number of sub-steps here. The kind of data that is either available or can be collected needs to be considered. Data use is often tied with the scale at which the work needs to be done. At the national level it will typically be necessary to rely on statistics and would not be possible to either find detailed data or it would be to expensive to start collecting it for a whole country. If, however, the focus is on a specific

Table 3 – A first selection of abstract indicators to include in the nitrogen causal network for our hypothetical example

Driving force	Mineral fertilizer prices; market demand for fertilizer demanding crops; market demand for organic crops (typically grown without mineral fertilizer)
Pressure	Mineral fertilizer use; organic fertilizer use; N emissions
State	N concentrations in air, water, soil; N run-off; N deposition; N leaching
Impact	Algae population; plant population; dissolved oxygen; water transparency; insect population; fish population; bird population
Response	Fertilizer regulations; stimulation of organic crop production

catchment it may be possible to find detailed data for that catchment or, at relatively low costs, set up a measurement program. There will typically be a tendency to rely on driving force and pressure indicators for national or global level analyses as these are often based on available statistical data or can be relatively easily estimated with some inferences. For more detailed studies, data on state and impact indicators may be more readily available. If good data is available, or measurement is a sensible solution, it may be necessary to make a choice in terms of where in the DPSIR chain the focus should be. If the objective is to know how serious a problem is, working with state or impact indicators is preferable, but if the objective is to know how best to control a situation, pressure and response indicators may be a more obvious focus. Finally, it needs to be determined whether an environment or human-centred perspective should be taken. For example, if the question relates to pollution, is the main interest the consequences for ecological system functioning or, first of all, the consequences for human health? The perspective taken will naturally affect indicator selection.

Returning to our nitrogen example, we might, for instance, want to answer the question what the impact of nitrogen eutrophication by crop production is on water quality of nearby surface water. With such a question, appropriate indicators at the cause and effects ends are most relevant, while remedies are less of a concern. For indicator selection it would obviously also be in important to refine the water quality concept by defining it in either environmental or human health terms (or both). Based on the domain of interest given in the previous section an environmental operationalization makes most sense in the context of our example.

- *Step 2. Identify key-nodes*: To use the causal network to help select appropriate indicators, it is necessary to start out by locating key-nodes in the causal network. There are three types of key nodes: root-nodes, central nodes and end-of-chain nodes. Root nodes are those nodes that have many outgoing arcs (the arcs diverge from these nodes). Fig. 2, because of its focus on crop production and nitrogen alone, does not have an example of this type of node, but it is not hard to image manure use having such a role considering that it is a source not only of nitrogen, but also of phosphorus and heavy metals. Central nodes are those nodes that have many incoming and/or outgoing arcs (converging and diverging arcs). Examples from Fig. 2 are the N concentrations node for the water compartment and the N emissions node. End-of-chain nodes typically have multiple incoming arcs (the arcs converge at these nodes) that bring together a number of longer chains. In Fig. 2, insect, fish and especially bird population are typical end-of-chain nodes.

Root nodes are important because their associated indicators typically provide information on the source of multiple issues or environmental problems. Central and end-of-chain nodes are important because the associated indicators will typically allow gauging the impact of multiple processes or issues at once. This is especially the case for end-of chain nodes, because they are located at the end of a series of cause-effect chains. Central nodes further have the characteristic that their associated indicators are also at the root of multiple processes. Indicators associated with key nodes with a large number of connecting arcs will typically be the most generally useful indicators since they are likely to have a bearing on a large number of issues and research questions.

Returning to our nitrogen question, we may want to start out by determining the water quality. If one is interested in water quality as such, indicators at end-of-chain nodes would be most useful, because these typically provide an overall picture of, in this case, water quality. However, such end-of-chain nodes are less useful to isolate a particular cause because indicators associated with end-of-chain nodes are typically influenced by multiple factors. This leaves two strategies, either (A) additional indicators will be needed that would provide evidence to exclude or correct for other factors causing changes in the end-of-chain indicator, or (B) one can move backwards through the network in order to identify nodes that bring together only process which have the same original cause. Below we will explore both strategies for our nitrogen example.

Strategy A: *looking for additional indicators*. If we start out with an end-of-chain indicator we need to identify what factors, in addition to the factor of interest (nitrogen eutrophication by crop production), influence this indicator. What other factors would have to be taken into account if bird population is the starting point? There would be factors such as bird nesting opportunities, or, in the case of migratory birds, problems occurring in the summer or winter environments they spend their time in. These factors are external to the studied water ecosystem and thus make bird population a less suitable indicator to use for water quality. With fish population that would be much less an issue, but even for that indicator there are other factors that affect the population outside of our nitrogen eutrophication problem and that need to be explored. To explore these factors, the water component of the causal network should be worked out in more detail as is done in Fig. 3.

Fig. 3 shows that at least four other possible sources of changes in the fish population should be considered: (1) namely P concentrations, which may also be affected by agricultural activities; (2) fine sediment load, which is related to erosion; (3) toxic substances, which may, for example, have an agricultural or industrial origin; (4) temperature regime, which is related to short-term and long-term climatic variations. Basically, this is the real-world complexity that is typically insufficiently captured by the causal chain focus of the current PSR frameworks. If the goal is to find the most effective indicator, this kind of complexity cannot and should not be ignored. At this point, contextual information will be needed to rule out certain factors and select correction indicators for other factors. With the term correction indicators, we are referring to indicators that are selected not because they have a direct bearing on the studied issue, but because they help correct for the influences of other factors than the one(s) of primary interest. Following logical inference and using contextual information about the research setting and research question, we can rule out temperature regime and fine sediment load. Short-term temperature fluctuations are not relevant if our study covers multiple years, and long-term fluctuations are likely to be so

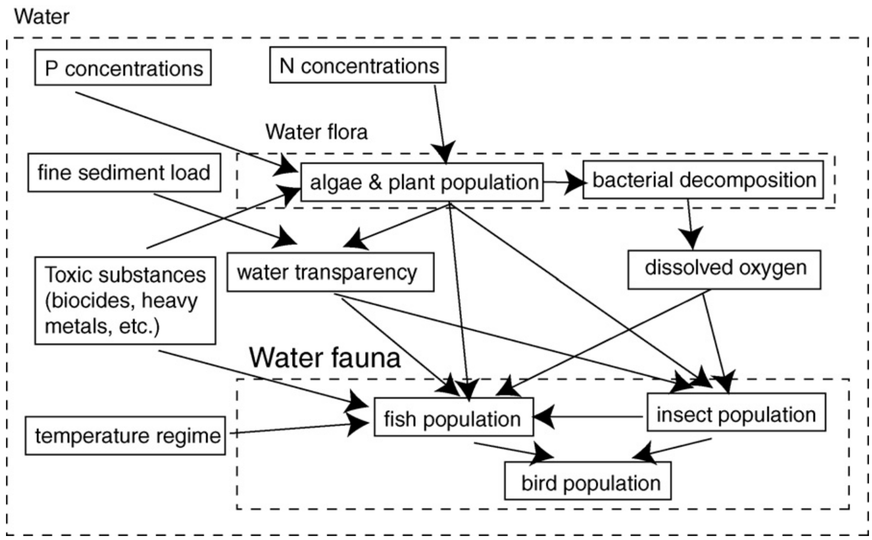

Fig. 3 – The water component of our sample causal network in more detail.

gradual that they can probably be ignored for the purpose of our analysis. In our Dutch setting we can in most cases rule out fine sediment load as a factor because the flat landscape does not lead to excessive erosion and therefore high fine sediment loads. This leaves nitrogen and phosphorus induced algae and plant growth as well as toxic substances as primary factors affecting fish population. If not near an industrial area, all of these factors are related to agriculture and to be more precise to mineral fertilizer use, organic fertilizer use and biocide use. This implies that if we want to isolate the nitrogen eutrophication cause for changes in fish population, we will need to have correction indicators for phosphorus, and various sources of toxification. Strategy A will thus require us to work with a number of additional indicators.

Strategy B: *moving backwards through the network*. If we want to keep our indicator set as small as possible, we will need to follow strategy B and trace-back from our end-of-chain node to one that only relates to nitrogen eutrophication. The node associated with N concentrations in the water perfectly fits that bill as can be seen in Fig. 2. This central node brings together the cause-effects paths from crop production related nitrogen emissions through water, air and soil and thus seems to be a perfect water quality indicator for our particular purpose.

Now that we have taken a look at the effects-end of the equation, we can move to the nodes at the cause-end. Here N fertilizer use would be an obvious choice requiring little argumentation. And, in case organic manure is applied we will also need an indicator for the amount of N spread over the fields in this way.

- *Step 3. Select the best indicators*: Now that key nodes have been identified with associated abstract indicators we need to identify the best concrete indicators to use for those nodes in the causal network. It is at this point that all the classic indicator selection criteria that were mentioned in Section 2.2 can be applied. However, even here one should not blindly select the indicator that best meets these criteria. The function of our indicator in analytical terms, that is, the role the indicator has in drawing the logical connections between cause and effect or correcting for other factors, should also be taken into account. It may in some cases be better to select an indicator that scores a little lower in terms of the individual evaluation criteria (such as those in Table 1) but is a corner stone in our logical inference of cause and effects.

By using the above approach indicators are selected such that each and every indicator has a particular function in telling the overall environmental story. Of course, indicators are always selected to communicate a particular point or to analyze a particular environmental problem. However, what the causal network helps to do, is to emphasize the function of the indicator and make it an explicit and key part of the indicator selection process. This approach also makes explicit that indicators only have relevance in conjunction with other indicators and within the context of a specific set of research questions (Niemi and McDonald, 2004). Only as part of a consistent and comprehensive set, can an indicator be interpreted effectively, without the risk of jumping to wrong conclusions on causes and effects. An indicator by itself is like a single data point in a graph, if there are no other data points in the graph there is no way of knowing the direction of the slope.

4. Conclusion

In this paper we have made two important critiques in relation to the indicator selection process in most indicator studies. First, that the selection process of environmental indicators is generally insufficiently systematic and transparent (Belnap, 1998; Slocombe, 1998; Dale and Beyeler, 2001; Bockstaller and Girardin, 2003; NCSSF, 2005). Second, that when studies do provide insight into the criteria used for indicator selection, they typically rely on criteria applied to individual indicators only and, with some exceptions, do not include criteria pertaining to the inter-relation of selected indicators (e.g., Schomaker, 1997; CBD, 1999; NRC, 2000; Pannell and Glenn, 2000; Riley, 2000; Kurtz et al., 2001; OECD, 2001; EEA, 2005a). Subsequently, it was argued that the utility and scientific credibility of indicator studies can be greatly enhanced if formal selection criteria are applied not just to indicators individually, but also in relation to an indicator's analytical utility within the total constellation of a selected set of indicators. This approach requires the selection process to be grounded in a conceptual framework that structures the interrelation of individual indicators.

The enhanced DPSIR (eDPSIR) framework (Niemeijer and de Groot, 2007) is proposed as a way to provide improved conceptual guidance in indicator selection, while building upon existing concepts such as the DPSIR approach, systems analysis, and causal networks. A major benefit of the proposed framework is that it does not consider individual causal chains but tackles the complexities of the real world by looking at causal networks in which multiple causal chains interact and inter-connect. Working with a causal network allows us to make use of the process-based knowledge used in modelling studies but typically left unexploited in indicator studies (Niemeijer, 2001).

The paper showed that, by constructing a causal network for a particular problem, it is possible to identify relevant indicators in a structured, yet flexible manner. At the same time the approach brings out the structural relation between indicators making this relation one of the key selection criteria. The traditional selection criteria applied to indicators individually (e.g., measurability, international compatibility) still have an important role to play, but only after the most crucial key nodes of the causal network have been identified. The approach outlined in this paper emphasizes the analytical function each indicator has in identifying, highlighting and monitoring environmental issues. It also lays the foundation for the development of powerful and transparent indicator sets that lead to relevant and more meaningful indicator-based analysis of the environment. Finally, by contributing to a more uniform approach to indicator selection, the eDPSIR framework can lead to more effective and consistent environmental reporting.

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