

The Beijer Institute of Ecological Economics

DISCUSSION PAPER

Beijer Discussion Paper Series No. 156

The Critical Natural Capital of Ecosystem Performance as Insurance for Human Well-being

Lisa Deutsch, Carl Folke, and Kristian Skånberg. 2002.

The critical natural capital of ecosystem performance as insurance for human well-being

Lisa Deutsch^{1,*}, Carl Folke^{1,2} and Kristian Skånberg³

¹ Natural Resources Management, Department of Systems Ecology, Stockholm University, S-106 91
Stockholm, Sweden

Tel: +46 8 161290 E-mail: lisad@system.ecology.su.se Fax: +46 8 158417

² Centre for Research on Natural Resources and the Environment (CNM), Stockholm University, and
Beijer International Institute of Ecological Economics, Royal Swedish Academy of Sciences,
Stockholm, Sweden

³ Swedish National Institute of Economic Research, Stockholm, Sweden

* Corresponding Author

Abstract

Complex dynamic ecosystems are important natural capital assets. We investigate how Swedish national policy has approached these assets in its work on environmental indicators. In particular, we are interested in whether or not the indicators address ecosystem performance. We discuss our inventory of Swedish indicators in the context of ecosystem services, such as source and sink functions, and the capacity of ecosystems to sustain these functions for human well-being. Effective indicators have been developed to reflect energy and material flows within society and how human activities put pressure on the environment. The part of natural capital that concerns living systems is reflected in several of the Swedish indicators in a progressive fashion, but indicators that capture the dynamic capacity of ecosystems in sustaining the flow of source and sink functions need to be further developed. We provide examples of recent developments that have started to address such indicators in the context of ecosystem resilience and environmental change, and discuss directions for their further development. We stress the importance of monitoring ecosystem resilience and performance to avoid undesirable state shifts and building ecological knowledge and understanding of this capacity into environmental indicators and their associated management institutions.

Key words: critical natural capital, environmental indicators, ecosystem performance, resilience, thresholds, source and sink functions

1. Introduction

An article in National Geographic (1998) displayed lights from human settlements on the planet at night taken from satellite images. The picture literally illuminated the fact that there are few places left on Earth where the human imprint is not evident. The rapid expansion of the scale of human actions has radically transformed the Earth (Turner et al., 1990). Due to this transformation, the capacity of life-support ecosystems to generate a flow of essential ecosystem services and maintain resilience in the face of disturbance is an increasingly limiting factor for societal development (Jansson et al., 1994; Holling et al., 1995; Folke et al., 1996,).

In this article, we focus on renewable natural capital, or more specifically, the role of complex, dynamic ecosystems as critical natural capital assets (Levin, 1999; Gunderson and Holling, 2002). ‘Criticality’ can be discussed in two ways in relation to ecosystems. There is critical natural capital in terms of essential environmental functions for human well-being (de Groot, 1992), functions referred to by some scholars as ecosystem services (Ehrlich and Mooney, 1983; Daily, 1997) or source and sink functions (Pearce and Turner, 1990; Ekins, 1992). But there is also critical natural capital in terms of environmental functions of ecosystems - or life-support functions - that reflect ecosystem performance. By ecosystem performance we mean the dynamic, often non-linear interrelations between populations and communities of plants, animals and microorganisms and their energetic, hydrological and biogeochemical environment. The life-support performance of ecosystems generates and sustains the flow of source-and-sink functions for our well-being and existence, as illustrated in Figure 1 (Limburg and Folke, 1999).

This article discusses the dynamic capacity of ecosystem life-support as a major “factor of production” for essential source-and-sink functions. In the first section, we investigate how Swedish national policy approaches this essential factor of production in its work on environmental and sustainability indicators. In particular, we are interested in whether or not the indicators address ecosystem performance and the capacity to sustain socioeconomic development. Next, we discuss the inventory in the context of a conceptual model that highlights the relation between source and sink functions for human well-being and ecosystem performance. Thereafter, we review recent findings on complex adaptive ecosystems in relation to ecosystem performance, critical natural capital and ecosystem capacity to sustain societal

development (Levin, 1999; Scheffer et al., 2001). We present current insights on how to develop indicators to capture essential variables in ecosystem performance dynamics, and use the concept of resilience (sensu Holling, 1973) as a unifying theme for this purpose. To avoid further loss of resilience and critical natural capital we then recommend a co-evolutionary approach to policy development (Norgaard, 1994), with institutional monitoring, understanding, and response to ecosystem dynamics as important components (Berkes and Folke, 1998; Berkes et al., 2002). This would be manifested in the active pursuance of adaptive co-management of the systems (Gunderson, 1999; Walters, 1997; Olsson and Folke 2001).

2. An inventory of Swedish natural capital indicators

We have compiled an inventory of Swedish indicators (Deutsch et al., 1999) that is summarized below. We found that many Swedish natural capital indicators are pressure indicators related to sink functions, but there are also state indicators and descriptions of the qualitative status of Swedish ecosystems. Some indicators are general, others reflect the societal metabolism, and a few address the processes of ecosystem performance. This is not surprising since the theory and understanding of complex dynamic ecosystems is recent (Levin 1999) and the knowledge of key structuring variables in ecosystem dynamics is under development (Gunderson and Pritchard 2002).

2.1 The Ministry of the Environment

In 1998, the Swedish Ministry of the Environment (Miljödepartementet) organized its environmental targets according to 15 national environmental quality goals (miljökvalitetsmålen) (Swedish Ministry of the Environment, 1998; Sustainable Sweden, 1999; Swedish Government, 1999):

1. Clean air,
2. High quality groundwater,
3. Sustainable lakes and watercourses,
4. Flourishing wetlands,
5. A balanced marine environment and a healthy coastline and archipelago,
6. No eutrophication,
7. Natural acidification only,
8. Living forests,
9. A rich agricultural landscape,
10. A majestic alpine environment,
11. A good urban environment,

12. A non-toxic environment,
13. Safe radiation levels,
14. A protective ozone layer,
15. A limited influence on climate change.

A 16th goal specifically for biodiversity is planned to be included in 2005 (Swedish Government, 2001).

The majority of these goals are directly linked to pressure indicators, i.e., goals 1, 2, 6, 7, 12-15. Goals number 3-5, 8 and 9 require understanding of ecosystem performance.

2.2 The Environmental Advisory Council to the Swedish Government

The Environmental Advisory Council to the Swedish Government (Miljövärdsberedningen) has presented a list of 12 sustainability indicators – ‘green headline indicators’ - deemed strategic for Sweden's conversion to an ecologically sustainable society (Environmental Advisory Council, 1998, 1999; SOU, 1998). These are intended as a complement to the 15 national environmental goals - but are designed specifically for policy makers and have three requirements: 1) easily understood, 2) affectable by policy decisions, and 3) make use of available data.

1. Electricity usage and efficiency in relation to GNP,
2. Materials usage and volume of disposed waste,
3. Usage of harmful chemicals,
4. Carbon dioxide emissions,
5. Emissions of acidifying substances,
6. Amount of Swedish nitrogen and phosphorous flows reaching the seas,
7. Benzene concentration levels in urban air,
8. Biodiversity index and protected forest areas as a share of productive forested land,
9. Choice of environmentally sound means of transport,
10. Value of environmentally sound purchasing,
11. Amount of phosphorous from sewage sludge used on cultivated land,
12. Number of enterprises and schools environmentally certified.

Indicator 8 concerns the management of ecosystem performance. Although there are implicit links to ecosystem performance, the remaining indicators focus on societal metabolism with impacts on environment. In the spring of 1999, all of these indicators were presented with actual data and a trend direction together with the Ministry of Finance's Report on the State of the Economy and the annual budget proposal. It is probable that Sweden is the first country in the world to do so (SOU, 1999).

2.3 Statistics Sweden

Statistics Sweden (Statistiska centralbyrån) continues its efforts to establish a System of Economic and Environmental Accounts (Statistics Sweden, 1998a; 1998b).

Examples we have seen proposed are pressure indicators:

1. Percentage of Swedish energy use from renewable sources.
2. Amount of carcinogenic and health-damaging substances used in economic sectors.
3. Amount of emissions from combustion.

2.4 The Swedish Environmental Protection Agency

The Swedish Environmental Protection Agency (SEPA) (Naturvårdsverket) has worked to establish state indicators for different ecosystems for some time. Indicators have been suggested for forests, freshwater ecosystems and urban air quality. Many of these indicators are of great relevance for source and sink functions, and they also address life-support functions. State indicators presented and suggested by the Swedish Environmental Protection Agency (SEPA 1992, 1994, 1996) include:

1. Indicators for forest areas.
2. Indicators for agricultural lands.
3. Indicators for wetlands.
4. Proposed indicators for mountainous areas.
5. Indicators for fresh water.
6. Proposed indicators for marine areas.
7. Indicators for the urban environment.

Additional suggested indicators include:

1. Biodiversity.
2. Improving efficiency of resource use.
3. The protection of green belts and cultural landscapes in urban areas.

Additionally, it is the SEPA that is responsible for monitoring and reporting on attainment of the 15 new Swedish Environmental Quality Objectives (Miljömålsrådet). Work to develop sustainability indicators for these 15 goals has been carried out by SEPA in conjunction with the Government Accounting Office and regional authorities, and is presented in reports on each specific goal. Assessment of the environmental quality goals is based on a framework originally presented by the Organisation for Economic Co-operation and Development (OECD) and then later

augmented by the European Environmental Agency (EEA) in conjunction with the National Institute of Public Health and Environmental Protection in the Netherlands (RIVM) called the **DPSIR** assessment and reporting framework (OECD, 1993; EEA, 1999; SEPA, 1999). It organizes indicators into five categories: **D**Driving forces, **P**Pressures, **S**States, **I**Impacts and **R**Responses. The SEPA has used this model to measure similar aspects:

- ?? national economic performance and its material metabolism are considered to be the main driving forces behind environmental pressures, including the use of natural resources and generation of emissions and waste,
- ?? pressures on Swedish ecosystems (flows of pollutants, land use practices),
- ?? states of Swedish ecosystems (stock variables),
- ?? impacts on economic outcomes and human welfare,
- ?? responses or measures taken to decrease pressures, improve states and decrease impacts.

2.5 The Swedish National Institute of Economic Research

The Swedish National Institute of Economic Research (Konjunkturinstitutet) has worked closely with Statistics Sweden and SEPA in the creation of the System of Economic and Environmental Accounts (Skånberg, 1998). The Institute works primarily with impacts on economic outcomes, but also on the effects of environmental pressures on human welfare and on the states of different Swedish ecosystems. Some present economic indicators include:

1. Costs for existing measures to reduce emissions of sulfur and nitrogen or decrease their effects on ecosystems, human health or human-made capital,
2. Annual cost estimates to reach environmental targets for emissions of sulfur and nitrogen set by the Ministry of the Environment,
3. Depreciation of (marketed) natural capital assets caused by sulfur and nitrogen emissions (i.e. acidification and eutrophication),
4. Willingness to pay for an improved environmental state resulting from reductions in sulfur and nitrogen emissions.

Newer measures included by the Institute are:

1. Forest accounts for 1987 and 1991,
2. An agricultural account (though not recent),
3. An environmental analysis of Swedish fisheries
4. A pilot study of water accounts.

2.6 Protected areas

To complement the indicators of the five government agencies, we examined the natural capital of several different ecosystems that have been set aside through the creation of reserves and protected areas in Sweden (see Table 1) (Statistics Sweden, 1998a; SEPA, 2000a). As of 2000, almost 4.1 million hectares of land are protected, an area equal to approximately 10% of Sweden's total land area (SEPA, 2000b).

Our inventory of natural capital indicators in Sweden illustrates that there is a predominance of indicators related to sink functions. They have evolved as a response to various human pressures (such as emission of waste and pollutants) and include measures of acidification, eutrophication and contamination. There are also indicators related to source functions such as water use estimates, forest accounts, and fish stock/production/catch levels.

Several indicators address the state of ecosystems, mainly as stock variables and often in terms of the area of an ecosystem type (e.g. wetlands, percentage of deciduous forests or boreal forests) or the amount of a characteristic of the area (e.g. number of dead stems per total stems in forest). In many respects the indicators of the Swedish EPA seem to appreciate that there are life-support functions of ecosystems. It is difficult to judge the extent to which the indicators capture internal ecosystem dynamics, or whether they have been developed for such a purpose. Nevertheless, the Swedish indicators are ambitious and of high quality relative to many other EU-nations. They explicitly recognize and acknowledge the importance of the living part of natural capital. They are in many respects in parity with recent scientific books on indicators (e.g. Schultze, 1999; Bell and Morse, 1999). As agreed upon by the Swedish Parliament, the 15 indicators should describe those aspects of the environment, including its natural and cultural resources, needed to obtain ecological sustainability. The overall goal is to provide the next generation with a society where the major environmental problems are solved. There is no doubt that the work with the various Swedish indicators strives towards improved management of natural capital.

3. The Swedish inventory in context

In this paper, we address natural capital criticality from two angles.

1. Critical natural capital in relation to environmental functions **for** human well-

being, i.e. source and sink functions, or ecosystem services.

2. Critical natural capital in relation to life-support functions **of** ecosystems, i.e. ecosystem performance and insurance to secure the flow of critical source and sink functions.

The first category of critical natural capital for human well-being concerns the flow or output from ecosystems (Figure 1). It is addressed in work on sustainability indicators and green accounting, for instance, as reflected in the accounts of the National Institute of Economic Research. The necessity of accounting for essential ecosystem services is increasingly recognized in policy by both governmental and private sectors.

The second category concerns the complex dynamics and interactions between plants, animals, microorganisms, and their environment that generate the flow of source and sink functions. The second category addresses the capacity of ecosystems to sustain ecosystem services, an issue in focus of the international UN-supported program the Millennium Ecosystem Assessment (www.millenniumassessment.org) that is connected to three international conventions. As will be illustrated in this article, resilience and biological diversity seem to play a key role in ecosystem performance and thereby provide the prerequisites for source and sink functions. This 'life-support criticality' is partly captured by de Groot's (1992) regulatory functions and Holling's (1973, 1996) concept of ecosystem resilience. Ekins et al. stress its importance in the framework paper of this special issue.

How do the Swedish indicators relate to these two categories? The 15 environmental quality goals are general and some of them (goals 3, 4, 5, 8 and 9) are directed towards ecosystem performance. The 12 sustainability indicators presented by the Environmental Advisory Council predominantly deal with material flows inside society and do not address ecosystem performance or criticality of life-support functions, with the exception of number 8. They do not specify renewable natural capital as a dynamic asset that needs to be monitored, understood and managed. The same is true of the Statistics Sweden indicators, and also of the measures primarily focused on by the Swedish National Institute of Economic Performance. Indicators have tended to be physical and monetary measurements of environmental pressures, and to some degree of environmental sink functions.

Encouragingly, the SEPA is in the process of developing state indicators of forests, agricultural lands, wetlands, mountainous areas, fresh water ecosystems, coastal areas,

and the urban environment. Also, the Swedish National Institute of Economic Performance has begun development of forest, water and fisheries accounts, and plans to update their agricultural accounts. Their approaches capture both source and sink functions, and in the future may also account for dynamic ecosystem performance and capacity. Recent insights on complex adaptive ecosystems (Levin, 1999) and the increasing understanding of the role of resilience in ecosystem capacity (Gunderson and Pritchard, 2002), as will be discussed below, may prove to be a useful framework in this context (Carpenter et al., 2001; Folke et al., 2002).

SEPA has been involved for some time in the establishment and management of protected areas and nature reserves, as have other Swedish agencies and NGOs. Protected areas capture parts of the life-support functions, and are critical as recruitment areas to surrounding landscapes, for the recovery of disturbed ecosystems, and for maintaining ecosystem resilience (Nyström and Folke, 2001; Bengtsson et al., in press). However, protected areas and reserves have historically often been established for other reasons, such as recreation or protection of certain species, rather than to secure critical links between source and sink functions and ecosystem performance. The dynamics of the ecosystem are often treated like a black box; this assumes that the ecosystem will function 'normally', i.e. that the system is fairly stable in relation to disturbance. However, several studies suggest that this assumption is no longer a safe one and that indicators of ecosystem functioning need to be made more explicit (Jackson et al., 2001; Scheffer et al., 2001).

Moreover, we have found no indicators, except for nutrient fluxes, that address critical links between ecosystems. These links include: water flows in the ecohydrological landscape upstream to downstream (Rockström et al., 1999); so-called 'mobile links' like migratory birds that prey on pest insects or transport seeds between systems (Baskin, 1997); and links that couple biodiversity to ecosystem performance (Cox et al., 1991; Walker et al., 1999; Nyström and Folke, 2001), such as the role of keystone species and insurance species (Folke et al., 1996; Naeem, 1998).

In the conceptual model in Figure 1, we suggest that the sustainability gap (Ekins et al., this issue) is wider than previously perceived. Swedish indicators have predominantly focused on measuring indicators in relation to sources and sinks. This is a necessary first step, but to conserve CNC in order to avoid undesirable state shifts, ecosystem performance should be addressed as well (Scheffer et al., 2001). The

concept of ecosystem resilience, and its antonym vulnerability (Kasperson and Kasperson 2001), provides a framework for analyzing performance (Carpenter et al., 2001). Adaptive management (Holling, 1978; Walters, 1986) may play an important role in this context. It is increasingly practiced in ecosystem management (Gunderson, 1999).

Nevertheless, we would like to praise the relative quality of Swedish indicators. They really strive towards improving management of renewable natural capital. It appears (see other articles in this special issue) that other researchers in the EU are hard-pressed to find established policy indicators of CNC. In the next section, we will present our perspective on how source and sink functions are linked to ecosystem performance.

4. Understanding the criticality of functioning ecosystems

Understanding the role of ecosystems as basic life-support systems has implications for management in a simple sense: societies must maintain sufficient levels of renewable natural capital, including its capacity to respond to change, to provide for their own needs for ecosystem services - the source and sink functions. If ecosystems were simple, then ecological-economic research would consist of finding and evaluating accurate production functions for ecological resources and services, and then fitting those functions into economic models and cost-benefit frameworks. Complex institutional arrangements governing ecosystem management would not be necessary for solving ecological problems (although they might be necessary to solve social and economic problems); institutions would chiefly govern the level or intensity of use. However, ecosystems are not simple systems close to a steady state.

4.1 Ecosystems as complex dynamic systems

Ecosystems are complex, self-organizing systems, nested across temporal and spatial scales (Levin, 1999). Because ecosystems have evolutionary components (rather than mechanistic) they exhibit a limited degree of predictability (Costanza et al., 1993). Further, because of the organizational and temporal complexity of ecosystems, human intervention can have different effects at different times, depending on which life-support functions are impacted (Redman, 1999; Jackson et al., 2001). In principle, there is an inherent unknowability, as well as unpredictability, concerning these evolving complex ecosystems (Gunderson 1999).

In recent years, several research groups have concentrated their efforts in trying to understand the dynamics of ecological systems and their linkages to social systems using the concept of resilience as a unifying theme (Holling, 1996). Resilience is the magnitude of disturbance that can be tolerated before an ecosystem moves into a different state with a different set of controls, i.e., the major processes and functions of the system are changed to the degree that a different set of ecosystem services, or even disservices, are generated by the system. Vulnerability is the antonym of resilience. Based on this interpretation, resilience has the following three properties: (a) the amount of change the system can undergo and still remain within the same state; (b) the degree to which the system is capable of self-organization (versus lack of organization or organization forced by external factors); and (c) the degree to which the system can build the capacity to learn and adapt. Adaptive capacity is a component of resilience that reflects the learning aspect of system behavior in response to disturbance.

Ecosystem research stresses the role of disturbance events, such as fire, storms, or pest outbreaks, as a part of ecosystem development (e.g. Turner et al., 1998). In a resilient system, disturbance has the potential to create opportunity for development by triggering reorganization and renewal. In a vulnerable system even a small disturbance may shift the ecosystem into an undesirable state, a shift which may cause severe social and economic consequences (Fig. 2). Although stochastic events like storms or fire can trigger shifts between ecosystem states, recent studies of, e.g., lakes, rangelands, oceans, coral reefs and forests show that it is the erosion of resilience that usually paves the way for a shift to an alternate, and often less desirable, state with a reduced capacity to supply ecosystem services (Scheffer et al., 2001).

For example, in lakes, water clarity often seems hardly affected by increased human-induced nutrient concentrations until a critical threshold is passed, at which point the lake shifts abruptly from clear to turbid, eutrophied waters (Scheffer et al., 1993; Carpenter et al., 1999). With this increase in turbidity, submerged plants disappear. The associated loss of animal diversity and reduction of the high algal biomass makes this state undesirable as activities like recreation or fisheries are affected. Substantially lower nutrient levels than those at which the collapse of the vegetation occurred are required to restore the system. Further, the economic and social intervention involved in such a restoration is complex and expensive (Mäler, 2000; Brock et al., 2002).

Similar human-induced shifts between states take place in rangelands. Rangelands shift between grass dominance and woody plants (small trees and shrubs) dominance. The shifts are driven by fire and grazing pressure under highly variable rainfall conditions (Walker, 1993). Persistent high grazing pressure for sheep or cattle production precludes fire. Above a certain density of woody plants, there is insufficient grass fuel to permit a fire and the rangeland shifts to the less productive (from a human use perspective) woody plant state. This pattern persists even when grazing animals are removed. It can take decades for the woody plant community to re-structure and open up sufficiently to allow fire back into the system (Ludwig et al., 1997).

Biological diversity plays a significant role in ecosystem performance and resilience (e.g. Peterson et al., 1998; Walker et al., 1999; Chapin et al., 2000; Loreau et al., 2001; Diaz and Cabido, 2001; Kinzig et al., 2002). This role is related to the diversity of functional groups of species in a system, like organisms that pollinate, graze, predate, fix nitrogen, spread seeds, decompose, generate soils, modify water flows, open up patches for reorganization and contribute to the colonization of such patches. Vertebrates that eat fruit, like flying foxes, play a key role in the regeneration of tropical forests hit by hurricanes or fire by bringing in seeds from surrounding ecosystems for reorganization and renewal (Cox et al., 1991; Elmqvist et al., 2001). Loss of such functional groups will severely affect the capacity of ecosystems to reorganize after disturbance and thereby impact on the flow of ecosystems services for human well-being. Such losses may even cause shifts into undesirable states as have been the case among coral reefs (Fig 3.).

Coral reefs in the Caribbean region have undergone dramatic changes, from a state dominated by hard coral to one dominated by fleshy algae (Knowlton, 1992; Hughes, 1994). The changes have been driven by a combination of hurricanes and disease with overfishing and nutrient increase from land-based human activities. The grazing of algae that fish species and other grazers perform contributes to the resilience of the coral reef. It keeps the substrate open for recolonization of coral larvae and thereby reorganizes the reef into coral-dominated state following disturbance events (Nyström and Folke, 2001). Continuous human exploitation of reef fish grazers (e.g. mammals, turtles, fish) (Jackson et al., 2001) led to increased abundance of a sea urchin species Diadema antillarum. The sea urchin became the keystone species within the functional group of grazers and could, despite high levels of nutrients in the water,

keep the density of invading algae low; thereby maintaining the coral-dominated state. However, when sea urchin populations were afflicted by a species-specific pathogen that reduced their numbers by 99% in some areas, then all major grazers were too few in number to prevent algae from invading and the reef changed to a state of algae dominance (Nyström et al., 2000).

Thus, the human use and abuse of coral reefs demonstrate how the loss of diversity through overfishing of species in the functional group of grazers resulted in eroded resilience and increased vulnerability. A disturbance event – the species specific pathogen - that previously could have been absorbed by a functional group with a diversity of herbivores, became the trigger that caused the ecosystem to shift from a coral-dominated state to one dominated by algae (Figure 3).

Such shifts, from one ecosystem state to another, may be virtually irreversible as in desertification, or periodic, as in the recurrent outbreaks of forest pests or diseases, such as influenza. The new state may not generate the same level, or even the same type, of source and sink functions as before, and thereby cause social and economic disruption.

5. Indicators of ecosystem resilience and performance

The recent findings related to resilience in ecological systems and how resilience is altered by human activities have implications for the identification of critical natural capital and associated indicators (Folke et al. 2002). Functional diversity in ecosystem resilience could from this perspective be viewed as natural insurance capital for spreading risks in the face of uncertainty and securing the generation of source and sink functions at present and in the future (Barbier et al., 1994).

The role of the 'insurance value' of biodiversity for societal development still remains to be embedded in work on environmental indicators. Indicators should be systemic and reflect the performance of not only a particular source or sink function, but also of the dynamic capacity of ecosystems, including their functional diversity, to respond to change and how this capacity relates to shifts between states. Without resilience renewable natural capital will deteriorate and lose its capacity to produce and sustain source and sink functions. In this sense maintaining resilience is maintaining critical natural capital.

Carpenter et al. (2001) argue that measures of resilience differ from environmental indicators as they are constructed at present. Resilience focuses on variables that

underlie the capacity of social and ecological systems to provide ecosystem services, whereas other indicators usually address the current state of the ecosystem or service.

Resilience measures under development relate to slowly changing variables that determine the boundaries beyond which disturbances may push the system into another state. The slowly changing variables include, e.g., land use, nutrient stocks, soil properties and biomass of long-lived organisms (Gunderson and Pritchard, 2002). For example, in the Great Lakes' District of North America the soil phosphorous content in the watershed is a slow variable that determines lake resilience and is strongly related to agricultural practices. Sediment phosphorous and the frequency of large runoff events are other important variables. In the rangelands of Western New South Wales, Australia, the woody vegetation cover is a slow variable related to soil moisture and is driven by land use practices and property rights arrangements (Carpenter et al., 2001). Previous management efforts have focused on more rapidly changing variables like water quality in the lakes or grass cover in the rangelands. It has taken several decades of research to acquire the understanding of the role of soils and phosphorous in lake eutrophication (Bennett et al., 2001). In rangelands, the increase of woody vegetation was episodic and often thought to be related to cycles of drought and flooding, loss of small native herbivores, large increases in kangaroo numbers or the introduction of rabbits. However, the fundamental cause was human removal of fire through herd management that shifted productive grasslands into woody states determined by soil moisture (Carpenter et al., 2001). Consequently, efforts to reduce the risk of undesired shifts between ecosystem states should develop indicators of ecosystem performance that address the gradual changes, the slow variables that affect resilience, rather than trying to control disturbance and fluctuations (Scheffer et al., 2001).

Indicators for monitoring and managing resilience will require understanding not only of the components of the systems, but their dynamic interactions over temporal and spatial scales (Gunderson and Holling, 2002). Furthermore, resilience indicators appropriate for the current state may become irrelevant as ecological structures and social expectations shift. Essentially, evolving systems, like complex adaptive systems (Levin, 1999), require policies and actions that not only satisfy social objectives, but at the same time achieve a continuously-modified understanding of the evolving conditions determining ecosystem resilience (Berkes et al., 2002). It is such

an understanding that should be reflected in indicators of ecosystem performance as critical natural capital.

6. Conclusions

We see a positive trend in the development of natural capital indicators. Presently, Swedish indicators are not only expanding from measurements of human waste emissions and harvesting of particular resources to adopting source and sink functions more broadly, but are now moving towards addressing ecosystems as dynamic and complex life-support systems for social and economic development and the importance of resilience in this context.

This is reflected in a unifying framework for nature management and policy in Sweden that was recently decided upon by the Swedish Government on March 14, 2002 (Swedish Government, 2002). In the section describing the basic philosophy behind the policy framework, it is stated that societal development depends on the capacity of ecosystems to sustain the flow of essential natural resources and ecosystem services and that this capacity provides the foundation for development. The report continues to state that this capacity needs to be conserved to sustain options for social and economic development and it requires an ability of ecosystems to buffer change, referred to as resilience. The role of biodiversity in this context is also highlighted in the report, as well as the need to involve local user groups and their knowledge systems (nature management closer to the citizens) in monitoring and management of ecosystem performance.

We envision that the development of indicators of ecosystem performance to capture critical natural capital in the context of resilience will become an increasingly important area for both research and policy in the coming years. Developments towards such indicators of ecosystem performance are presently taking place, for example, through the work of the Millennium Ecosystem Assessment with its focus on strengthening capacity for managing ecosystems sustainably for human well-being.

Acknowledgements

Financial support was provided by the European Commission DGXII project number PL9702076, entitled: “Making Sustainability Operational: Critical Natural Capital and the Implications of a Strong Sustainability Criterion (CRITINC)”.

References

- Barbier, EB, Burgess, J and Folke, C., 1994. *Paradise Lost? The Ecological Economics of Biodiversity*. Earthscan, London.
- Baskin, Y., 1997. *The Work of Nature: How the Diversity of Life Sustains Us*. The Scientific Committee on Problems of the Environment, Washington, D.C.
- Bell, S and Morse, S., 1999. *Sustainability Indicators: Measuring the Immeasurable?* Earthscan Publications Ltd, London.
- Bengtsson, J., Angelstam, Elmqvist, T, Emanuelsson, U, Folke, C, Ihse, M, Moberg, F, and Nyström, M., In press. Dynamic nature reserves as a tool for biodiversity conservation and ecosystem management. *Ambio*.
- Bennett E.M., Carpenter S.R. and Caraco, N.F., 2001. Human impact on erodable phosphorus and eutrophication: a global perspective. *BioScience*, 51:227-234.
- Berkes, F. and Folke, C. (Editors), 1998. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. Cambridge University Press, Cambridge, UK.
- Berkes, F., Colding, J., and Folke, C. (Editors), 2002. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. Cambridge University Press, Cambridge.
- Brock, W.A., Mäler K.-G. and Perrings, C., 2002. Resilience and sustainability: The economic analysis of nonlinear systems. In: Gunderson, L.H. and Holling, C.S. (Editors), 2002. *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press, Washington, D.C.
- Carpenter, S.R., Ludwig, D. and Brock, W.A., 1999. Management of eutrophication for lakes subject to potentially irreversible change. *Ecol. Appl.*, 9:751-771.
- Carpenter, S.R., Walker, B., Anderies, J.M. and Abel, N., 2001. From metaphor to measurement: Resilience of what to what? *Ecosystems*, 4:765-781.
- Chapin, F.S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., and Diaz, S., 2000. Consequences of changing biodiversity. *Nature*, 405:234-242.
- Costanza, R., Waigner, L., Folke, C., and Mäler, K.-G., 1993. Modeling complex ecological economic systems: toward an evolutionary dynamic understanding of people and nature. *BioScience*, 43:545-555.

- Cox, P.A., Elmqvist, T., Rainey, E.E. and Pierson, E.D., 1991. Flying foxes as strong interactors in South Pacific Island ecosystems: A conservation Hypothesis. *Conservation Biology*, 5:448-454.
- Daily, G. (Editor), 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Washington DC.
- de Groot, R.S., 1992. *Functions of Nature*. Wolters-Noordhoff, Amsterdam.
- Deutsch, L., Folke, C., and Skånberg, K., 1999. Appendix 1: Swedish Critical Natural Capital: an inventory of existing indicators and goals. Report for European Commission DGXII project number PL9702076, entitled: "Making Sustainability Operational: Critical Natural Capital and the Implications of a Strong Sustainability Criterion (CRITINC)".
- Diaz, S. and Cabido, M., 2001. Vive la difference: plant functional diversity matters to ecosystem processes. *Trends Ecol. Evol.*,16:646-655.
- EEA, 1999. *Environment in the European Union at the turn of the Century*. European Environment Agency, Copenhagen, Denmark.
- Ehrlich, P.R. and Mooney, H.A., 1983. Extinction, substitution and ecosystem services. *BioScience*, 33:248-254.
- Ekins, P. 1992. A four-capital model of wealth creation. In: Ekins, P. and Max-Neef, M. (Editors), 1992. *Real-Life Economics: Understanding Wealth Creation*. Routledge, London.
- Elmqvist, T., Wall, M., Berggren, A.L., Blix, L., Fritioff, S. and Rinman, U., 2001. Tropical forest reorganization after cyclone and fire disturbance in Samoa: remnant trees as biological legacies. *Conservation Ecology*, 5(2):10. [online] Available at URL: <http://www.consecol.org/vol5/iss2/art10> .
- Environmental Advisory Council, 1998. Miljöårsberedningen, regeringskansliet press release 1998-10-23.
- Environmental Advisory Council, 1999. *Green Headline Indicators – Monitoring Progress towards Ecological Sustainability*. English summary brochure of official Government documents SOU 1999:127 and SOU 1998:170. Available at URL: http://www.hallbarasverige.gov.se/eng/vagar_till/miljovard/green_hdl_indictrs.pdf.
- Folke, C., Holling, C.S. and Perrings, C., 1996. Biological diversity, ecosystems, and the human scale. *Ecol. Appl.*, 6:1018-1024.
- Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S., Walker, B., Bengtsson, J., Berkes, F., Colding, J., Danell, K., Falkenmark, M., Moberg, F.,

- Gordon, L., Kaspersson, R., Kautsky, N., Kinzig, A., Levin, S.A., Mäler, K.-G., Ohlsson, L., Olsson, P., Ostrom, E., Reid, W., Rockström, J., Savenije, S., and Svedin, U., 2002. Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. ICSU Series on Science for Sustainable Development No. 3, 2002. International Council for Science, Paris.
- Gunderson, L.H., 1999. Resilience, flexibility and adaptive management -- Antidotes for spurious certitude? *Conservation Ecology*, 3(1):7 [online] Available at URL: <http://www.consecol.org/Journal/vol3/iss1/art7/> .
- Gunderson, L.H. and Holling, C.S.(Editors), 2002. *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press, Washington, D.C.
- Gunderson, L.H. and Pritchard, L. (Editors), 2002. *Resilience and the Behavior of Large-Scale Ecosystems*. Island Press, Washington, D.C.
- Holling, C.S., 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4: -23.
- Holling, C.S. (Editor), 1978. *Adaptive Environmental Assessment and Management*. Wiley, London.
- Holling, C.S., Schindler, D.W., Walker, B.H. and Roughgarden, J., 1995. Biodiversity in the functioning of ecosystems: an ecological synthesis. In: Perrings, C.A., Mäler, K.-G., Folke, C., Holling, C.S. and Jansson, B.-O. (Editors), 1995. *Biodiversity Loss: Economic and Ecological Issues*. Cambridge University Press, Cambridge, UK.
- Holling, C.S., 1996. Engineering resilience versus ecological resilience. In: P.C. Schulze (editor). *Engineering within Ecological Constraints*. National Academy Press, Washington, D.C.
- Hughes, T.P., 1994. Catastrophe, phase shifts and large-scale degradation of a Caribbean coral reef. *Science*, 226:1547-1549.
- Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandsson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J. and Warner, R.R. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science*, 293: 629-638.
- Jansson, A.M., Hammer, M., Folke, C. and Costanza, R.(Editors), 1994. *Investing in Natural Capital: The Ecological Economics Approach to Sustainability*. Island Press, Washington D.C.

- Kasperson, J.X. and Kasperson, R.E. (Editors), 2001. *Global Environmental Risk*. United Nations University Press/Earthscan, London.
- Kinzig, A.P., Pacala, S.W. and Tilman, D. (Editors), 2002. *The Functional Consequences of Biodiversity*. Princeton University Press, Princeton, N.J.
- Knowlton, N., 1992. Thresholds and Multiple Stable States in Coral Reef Community Dynamics. *American Zoologist*, 32:674-682.
- Levin, S., 1999. *Fragile Dominion: Complexity and the Commons*. Perseus Books, Reading, MA.
- Limburg, K. and Folke, C., 1999. The ecology of ecosystem services: introduction to the special issue. *Ecol. Econ.*, 29:179-182.
- Loreau M, Naeem S, Inchausti P, Bengtsson J, Grime JP, Hector A, Hooper DU, Huston MA, Raffaelli D, Schmid B, Tilman D, and Wardle DA. 2001. Biodiversity and ecosystem functioning: Current knowledge and future challenges. *Science*, 294:804-808.
- Ludwig, D., Walker, B., and Holling, C.S., 1997. Sustainability, stability and resilience. *Conservation Ecology* 1(1):7 [online] Available at URL: <http://www.consecol.org/vol1/iss1/art7> .
- Mäler, K.-G., 2000. Development, ecological resources and their management: A study of complex dynamic systems. *European Economic Review*, 44: 645-665.
- Naeem, S., 1998. Species redundancy and ecosystem reliability. *Conservation Biology*, 12:39-45.
- National Geographic Magazine, October 1998. Special insert.
- Norgaard, R.B., 1994. *Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future*. Routledge, London.
- Nyström, M. and Folke, C., 2001. Spatial resilience of coral reefs. *Ecosystems*, 4:406-417.
- Nyström, M., Folke, C. and Moberg, F., 2000. Coral-reef disturbance and resilience in a human-dominated environment. *Trends Ecol. Evol.*, 15: 413-417
- OECD, 1993. *OECD Core Set of Indicators for Environmental Performance Reviews*. Environmental monographs no. 83. OECD, Paris. Accessed via internet <http://www.oecd.org/env/docs/gd93179.pdf> .
- Olsson, P. and Folke, C., 2001. Local ecological knowledge and institutional dynamics for ecosystem management: A study of Lake Racken watershed, Sweden. *Ecosystems*, 4:85-104.

- Pearce, D and Turner, R. K., 1990. Economics of Natural Resources and the Environment. Harvester Wheatsheaf, Hemel Hempstead, UK.
- Peterson, G.D., Allen, C.R. and Holling, C.S., 1998. Ecological resilience, biodiversity, and scale. *Ecosystems*, 1:6-18.
- Redman, C.L., 1999. Human Impact on Ancient Environments. The University of Arizona Press, Tucson, AZ.
- Rockström, J., Gordon, L., Folke, C., Falkenmark, M. and Engvall, M., 1999. Linkages among water vapour flows, food production and terrestrial ecosystem services. *Conservation Ecology* 3(2):5. [online] Available at URL: <http://consecol.org/vol3/iss2/art5>).
- Schultze, P.C. (Editor), 1999. Measures of Environmental Performance. National Academy of Engineering, Washington, DC, 303 pp.
- Scheffer, M., Hosper, S.H., Meyjer, M.-L., Moss, B. and Jeppsen, E., 1993. Alternative Equilibria in Shallow Lakes. *Trends Ecol. Evol.*, 8:275-279.
- Scheffer, M., Carpenter, S.R., Foley, J., Folke, C. and Walker, B., 2001. Catastrophic shifts in ecosystems. *Nature*, 413:591-696.
- SEPA, 2000a. Naturvårdsregister.
- SEPA, 2000b. Internet homepage URL: <http://www.environ.se:8084/>
- SEPA, 1999. System för uppföljning av miljö kvalitetsmålen. 99-06-15. Available at URL: <http://www.environ.se/milmalnet98/uppf/slutrap8.pdf> . In Swedish.
- SEPA, 1997. Ren luft och gröna skogar - förslag till nationella miljömål, report no. 4765.
- SEPA, 1996. Miljö tillstånd och miljö kvalitet – förslag till officiell statistik, report no. 4650.
- SEPA, 1994. Ett svenskt miljöindexsystem, lägesrapport 2 till regeringen, Mm, (1994-10-20)
- SEPA, 1992. Hur mår Sverige år 2020, rapport 4104, (1992)
- Skånberg, K., 1998. The environmental accounting project at the National Institute of Economic Research 1992-1997. Konjunkturinstitutet.
- SOU, 1998. Förslag till gröna nyckeltal för ett ekologiskt hållbart samhälle 1998:15. (available from the Internet. URL: http://www.miljo.regeringen.se/propositionermm/sou/pdf/sou98_15.pdf).

- SOU, 1999. Gröna nyckeltal – följ den ekologiska omställningen, 1999:127.
(available from the Internet. URL: <http://www.hallbarasverige.gov.se/pdf/mvb-nyckeltal-rapp.pdf>).
- Statistics Sweden, 1998a. Skyddad natur 31 dec 97. Na 41 SM 9801.
- Statistics Sweden, 1998b. SWEEA. Swedish Economic and Environmental Accounts. English version 1994, report no. 1998:2.
- Statistics Sweden, 1998c. Samband mellan ekonomi och miljö, Miljöräkenskaper rapport 1998:6.
- Sustainable Sweden, 1999. (Hållbara Sverige) website: Swedish environmental quality objectives – English summary. Accessed April 22, 1999. Available at URL: http://www.hallbarasverige.gov.se/cgi-bin/hs_utflykt_e.cgi?&tibax=www.hallbarasverige.gov.se/eng/vagar_till/miljomal/miljomal.htm&ut=miljo.regeringen.se/pressinfo/pdf/p9798_145e.pdf
- Swedish Government, 1999. Hållbara Sverige – uppföljning av åtgärder för en ekologiskt hållbar utveckling. (Sustainable Sweden – A progress report on measures to promote ecologically sustainable development). Regeringens skrivelse 1999/2000:13.
- Swedish Government, 2001. Svenska miljömål – delmål och åtgärdstrategier (Swedish environmental quality goals – sub-goals and strategies). Regeringens skrivelse 2000/01:130. Available at URL: http://miljo.regeringen.se/M-dep_fragor/hallbarutveckling/miljokvalitetsmal/p200001_130.PDF
- Swedish Government, 2002. En samlad naturvårdspolitik (A unified nature management policy). Regeringens skrivelse 2001/02:173. Available at URL: http://miljo.regeringen.se/propositionermm/skrivelser/pdf/skr200102_173.pdf
- Swedish Ministry of the Environment, 1998. Press release 58/98.
- Turner, B.L., Clark, W.C. and Kates, W.C. (Editors), 1990. The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Last 300 Years. Cambridge University Press, Cambridge, UK.
- Turner, M.G., Baker, W.L., Peterson, C.J., and Peet, R.K., 1998. Factors influencing succession: lessons from large, infrequent natural disturbances. *Ecosystems*, 1:511-523.
- Walker, B.H., 1993. Rangeland ecology: understanding and managing change. *Ambio*, 22:80-87.

Walker, B., Kinzig, A. and Langridge, J., 1999. Plant Attribute Diversity, Resilience, and Ecosystem Function: The Nature and Significance of Dominant and Minor Species. *Ecosystems*, 2:95-113.

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D. and Pritchard, L. Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Conservation Ecology* in press.

Walters, C.J., 1986. *Adaptive Management of Renewable Resources*. Mc-Graw Hill, New York.

Walters, C., 1997. Challenges in adaptive management of riparian and coastal ecosystems. *Conservation Ecology* 1(2):1. Available at URL: <http://www.consecol.org/vol1/iss2/art1>).

Table 1. Protected natural areas in Sweden

All figures in hectares:

Total land area protected: 4,073,111

These areas are protected as:

	Total area protected (ha)	Land area protected (ha)
Natural parks (N=26) ¹	652,395	590,681
Nature reserves (2192) ¹	3,893,654	3,273,867
Conservation areas (140) ¹	223,914	146,071
	<hr/> 4,769,963	<hr/> 4,010,619

Additional areas not included above:

Wildlife sanctuaries (1049) ¹	107,617	60,659
Biotopes protected (752) ²	1,833	1,833
	<hr/> 109,450	<hr/> 62,492

¹SEPA, 2000a.

²Statistics Sweden, 1998a.

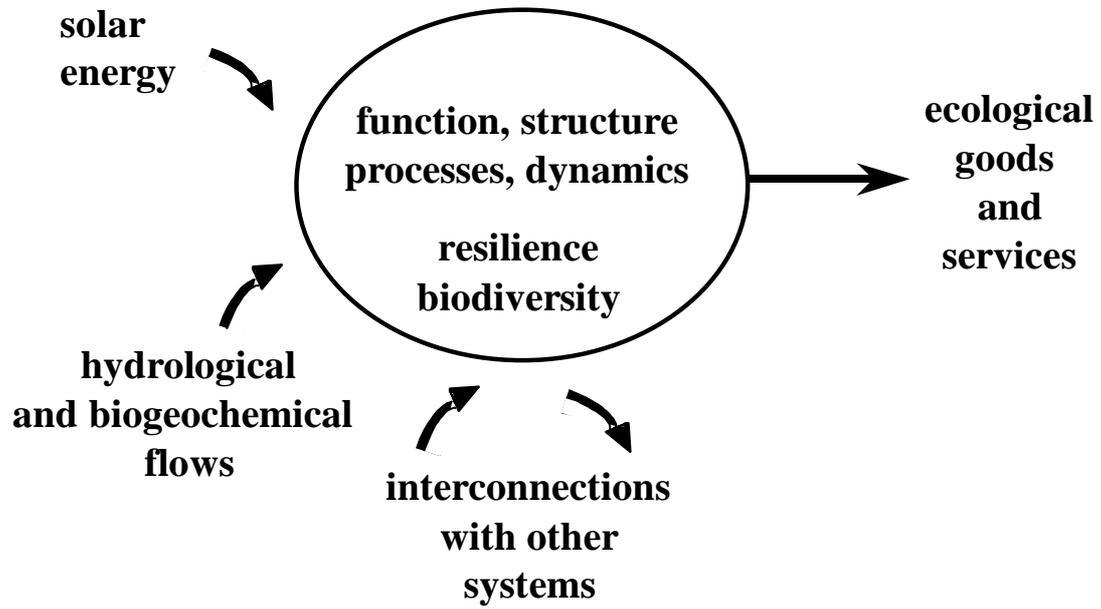
Captions to illustrations:

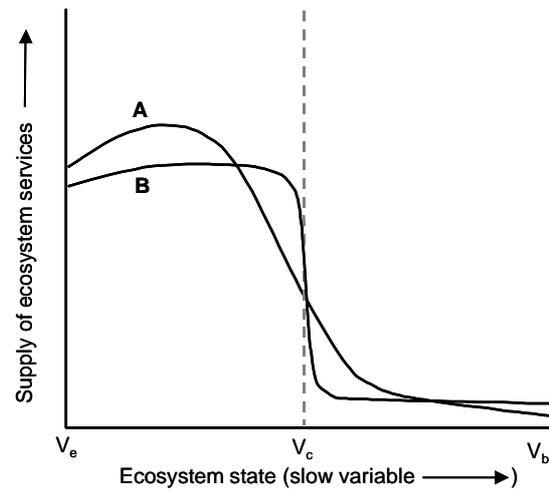
Fig. 1. The life-support performance of ecosystems generates and sustains the flow of source and sink functions for our well-being and existence.

Fig. 2. Ecosystem shifts and associated reduction of ecosystem services. 'A' represents rangeland ecosystem services (wool production) from grazing as a function of woody vegetation biomass (W). 'B' represents lake ecosystem services (fish, recreation) as a function of phosphorous (P) in lake sediment and agricultural soil in the catchment. V_c is the critical, threshold level of W and P. It demarcates a shift from one ecosystem state to another and the consequent loss of ecosystem services. Indicators that reflect ecosystem performance and resilience are needed to avoid undesirable state shifts (based on Walker et al., in press).

Fig. 3. Complex ecosystems tend to have more than one state and can slide between states (Scheffer et al., 2001). For example, in 1) the reef is in a state of coral dominance. In 2) the reef is still dominated by corals, but ecosystem resilience is eroding as a consequence of human activities (e.g. fisheries exploitation reduces diversity within the functional group of grazers and eutrophication from human activities on land increases algal growth). Consequently, 3) the system is progressively becoming more vulnerable to disturbances that previously could be absorbed (e.g. hurricanes and diseases). Such events might now push the reef into an undesirable state of algal dominance 4) and cause loss of essential ecosystem services. See text for the lake and grassland case.

Complex Adaptive System





Multi-equilibrium view

