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Indicating ecosystem and landscape organisation

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Abstract

This paper presents a brief outline of the theoretical and conceptual fundamentals for the derivation of an ecosystem oriented indicator system to demonstrate the state of ecological entities on a holistic basis. There are two branches of argumentation: on a normative level, the sustainability principle is interpreted from an anthropocentric point-of-view; sustainability in this context means to provide ecosystem services on a broad scale and a long-term basis, including the attempt to avoid unspecific ecological risks. A second line-of-argumentation bases on the principles of ecosystem analysis and the theory of ecological orientation. Consequently, the aspired indicandum is the self-organising capacity of ecosystems, and the indicator sets represents an aggregate of structural and functional ecosystem features in a developing environment. The indicator set is demonstrated by one case study from the Bornhoeved Lakes ecosystem research project.

Keywords: Ecosystem analysis; Ecosystem organisation; Ecological indicators; Landscape indicators; Ecological orientors; Sustainable development

1. Introduction

The guiding principle of contempory environmental management is a holistic principle: the idea of sustainable development implies several demands which can only be fulfilled within an interdisciplinary, systems-based framework that takes into account the social, economic, cultural and ecological features of many interacting temporal and spatial scales, reaching up to long-term (intergenerational) and global (intragenerational) issues (Hauff, 1987; WCED, 1987). An important lesson from ecosystem analysis and ecosystem restoration states that these pretentious holistic requirements can only be met if indirect, chronical and de-localised effects are treated as focal elements of the respective scientific investigations and political activities (Costanza, 2000; Daily, 1997; Joergensen, 1992; Patten, 1992). Otherwise the long-term aspects of the sustainability principle cannot be transferred correctly, decision supporting scenarios cannot be conducted reliably, and the resulting political concepts will be incomplete and short-sighted. Thus, besides the demanded spatial and temporal extents, sustainable development also requires deep substantial extents, considering multiple subsystems and elements as well as the prevailing interrelations between them.

These theses may provoke various consequences for environmental indication, i.e. they underline the

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necessities for holistic conceptions and for the application of ecological systems analysis. The following paper is an attempt to present one approach for a holisitic indication of ecological items on the ecosystem and on the landscape scale. Realising the basic requirements for indicators (e.g. political relevance, representativity, validity, sensitivity, transparency, applicability, etc.; see Wiggering and Müller, 2003), the described concept tries to represent the organisational states of ecological systems using a minimum set of indicators, which have been derived on a holistic ecosystem theoretical basis. The target of the indicator set is to provide a general quantifying representation for the integrity of ecological systems. The focal questions of the paper are the following:

(1) Is it possible to represent ecosystem and landscape states on the base of a small number of variables?
(2) Is it possible to formulate eco-targets for ecosystem and landscape management on the base of ecosystem theories?
(3) Is it possible to derive applicable indicators from applied theoretical considerations?
(4) Which problems will arise concerning the indicators' applications?

The paper will start with a terminological discussion. It includes a sequence of expressions leading through the concepts of ecological sectors, structures, functions and organisation. Throughout that ''zoom'' over ecological levels-of-integration there will be the attempt to build a bridge to the socio-economic side of sustainability with the concept of ecosystem services. On this base, a holistic indicandum will be introduced: ecological integrity as an ecological branch of sustainability. Thereafter, the guidelines of the indicator derivation and the proposed indicator set to represent ecosystem organisation will be described. After brief descriptions of some case studies, the introductory questions will be discussed and some conclusions will be drawn.

2. The starting point: what is ecosystem organisation?

Taking into account the targets of this volume—a discussion of functional and structural landscape indicators, and the goals of this paper—the development of a holistic indicator set to represent ecosystem and landscape states, some basic terms have to be pointed out in the beginning, i.e. due to the extraordinary multitude of comprehensions concerning the focal conceptions of this approach. Therefore, we will start with a short definition of the expressions sector, structure, function and organisation.

Traditionally, ecologists are investigating different *sectors* of ecosystems: they try to find out basic characteristics of isolated ecosystem compartments, such as vegetation, fauna, microflora, soils, aquifers or other—often smaller observer defined subsystems. The fundamental features of these units are illuminated in a very detailed style, often reducing the number of potential influences between the elements of the investigated systems. Most of the actually used indicator systems can be assigned to this sectoral, mono-disciplinary approach and also the interpretations of the achieved indicator values mostly are restricted to the fate of very specific subsystems of the observed ecological entities from an isolating, reductionistic viewpoint.

If we look at the integral composition and the spatial arrangement of such subsystems, *structural investigations* are conducted. Typical questions of this approach are the following: Which are the relevant components, elements or subsystems to answer the observer's questions? Which are the relevant spatial or temporal patterns of these elements? Which is the species composition of the investigated system? Which are the significant habitat features and which determining abiotic patterns can be found in the landscape? Such questions are leading to indicator sets about slowly changing variables, which are established on inventories, regional accountings or other geographical methods (see Golley, 2000).

While these structural approaches are analysing the ''processors'' of the system, the investigation of ''pure'' *ecological functions*[1] aims at the processes

[1] Of course, the term ''function'' implies many different comprehensions, such as the general activity or performance of a system, the role of an object, its specific task, the purpose of an entity or mathematical interrelations (see Jax, 2000; Müller and Windhorst, 2000). In the context of the approach described in this paper, ''ecosystem functions'' are reduced to the processual interrelationships between the elements or subsystems of an ecological entity. This renunciation of a normative, utilitaristic or teleological component in the understanding of ''function'' has lead to the attribute ''pure''.

that link the structural elements, the interactions between the "processors". Thus, ecosystem functions constitute the web of relations within the system (Jax, 2000; Filser, 2002; Müller and Windhorst, 2000). Typical functional questions are these: Which are the relevant processes in the system? Which are the respective storages and pools of energy or nutrients? Which are the flows between these pools? Which are the dynamic developments of the processes? How are these processes regulated? The respective indicators are referring to energy budgets, nutrient dynamics, ecotoxicological effects or hydrological variables. The structural items are integrated into functional analyses, taking the role of border conditions or pools.

This last aspect leads us to the even more integrative question how the whole ensemble of flows, storages and regulations is organised. To understand that item, both structures and functions have to be taken into account. With this conceptual step, we are operating on the ecosystem level.[2] The aggregate of the structural and the functional aspects constitutes *ecosystem organisation*, a term with a twofold connotation. Organisation on the one hand is directed towards the process of gaining order and towards the result of this process on the other. Organisation thus defines the act of forming a whole from interdependent subunits as well as the emerging arrangement of the parts. This leads to a specific performance of the system's functions and to a certain trend in its development.

As the respective order of ecological systems emerges from spontaneous processes and as the organising processes can operate without consciously regulating influences from the system's environment, the development of ecosystems is assigned to the category of *self-organisation* processes which actually are constrained by human activities (see Müller et al., 1997a,b; Müller and Nielsen, 2000). These constraints may be able to reduce the degrees of freedom for ecosystem development, but the self-organised processes usually can not be set aside. An indication for ecosystem self-organisation has been proposed in a small number of case studies only. They are referring to the concepts of ecosystem health (Rapport, 1989; Haskell et al., 1993; Rapport and Moll, 2000) or environmental integrity (Karr, 1981; Woodley et al., 1993). Besides multi-variate approaches (Schneider and Kay, 1994; Kay, 1993, 2000) and aggregated ideas (Costanza, 1993) some authors propose to use extremely integrating, theory based variables like exergy (Joergensen, 2000), emergy (Odum et al., 2000; Ulgiati et al., 2003) or ascendancy (Ulanowicz, 2000) These bright concepts are very original, they are discussed very actively, but there are tremendous problems, data requirements and modelling demands when trying to apply them in practice. One unifying factor of this level of indication is the consciousness of holistic necessities, as they are, e.g. expressed in the survey of Haskell et al. (1993), which is documented in Table 1.

One result of the described self-organised, autonomous processes in the ecosphere is the potential of utilizing the outputs of ecosystems' performances by man; ecosystem structures and functions provide certain *environmental services*[3] which are the benefits people obtain from ecosystem organisation, thus being basic requirements for human life (see Costanza et al., 2000; Millenium Assessment Board, 2003).[4] With this approach, we are adding a normative level of evaluation, which is based on the potential contributions of ecosystem organisation for the benefit of human society. One potential classification of these services is based on the works of De Groot (1992). From his point-of-view the performance of ecosystems can be distinguished into the following classes:

- *General provisions (carrier services)*: Ecosystem structures are providing space and suitable substrates for human activities. Examples for these land use oriented services are the carrierships for

[2] Ecosystems are understood as models of networks consisting of biotic and abiotic interactions in a certain area (see Joergensen and Müller, 2000; Müller and Breckling, 1997). To understand their general features and to validate the implicit models, structural and functional components have to be combined. As it is strictly based on conceptual models, the ecosystem approach can be applied on all scales, if the scheme of interrelations and the dynamics of the respective structures are included within the investigations.

[3] In many concepts, ecosystem services are nominated "ecosystem functions" (De Groot, 1992; Müller and Windhorst, 2000). To avoid misunderstandings, the term "function" will be used here only in the sense of "pure" ecological interactions.

[4] The Millenium Assessment Board (2003) distinguishes provisioning services (e.g. food and water), regulating services (e.g. flood and disease control), cultural services (e.g. spiritual, recreational and cultural benefits) and supporting services.

Table 1
Fundamental axioms of ecosystem health, after Haskell et al. (1993)

Dynamism	Nature is a set of processes, more than a compilation of structures
Relatedness	Nature is a network of interactions
Hierarchy	Nature is built up by complex hierarchies of spatio-temporal scales
Creativity	Nature consists of self-organising systems
Different fragilities	Nature includes various sets of different resiliences

These features can also be taken as general guidelines for the construction of holistic, ecosystem based indicator systems.

habitation, cultivation or tourism. All of them are dependent on certain ecological preconditions, thus the potential of a spatial entity to provide these items is determined by the actual ecological state, which results in the systemic interrelations of ecosystems. Carrier services can be indicated by landuse structures.

- *Products*: Ecosystem development provides natural resources for human use. Ecosystemic compartments like carbon pools for food, oxygen or fuel are examples for such natural products. They can be indicated by resource utilisation accountings and statistics.
- *Information*: Ecosystems are providing cultural attributes. The respective services result in education, aesthetics, history or emotional attributes. Information services can be indicated by socio-economic parameters.
- *Regulations*: Ecosystem functions are regulating the availability of basic demands for human life. All ecological processes can be assigned to this category as they buffer external influences in a way that enables man to continue life in an environment with suitable climatic, chemical and physical conditions. Examples for these services are climatic regulations, the regulations of energy, water and matter budgets and also the organisation of ecological or agricultural production processes. These items are the focal points of the indicator set presented in this paper.

Taking a synoptical look at these four categories, one fact becomes obvious that all ecosystem services are strongly dependent on the performance of the regulation functions. The correlated processes do not only influence production rates, but on the long run they also determine the potentials of ecosystems to provide carrier and information services. And if we finally link all argumentations of this chapter, it becomes clear that the respective benefits are strictly dependent on the degrees and the potentials of the fundamental self-organising processes.

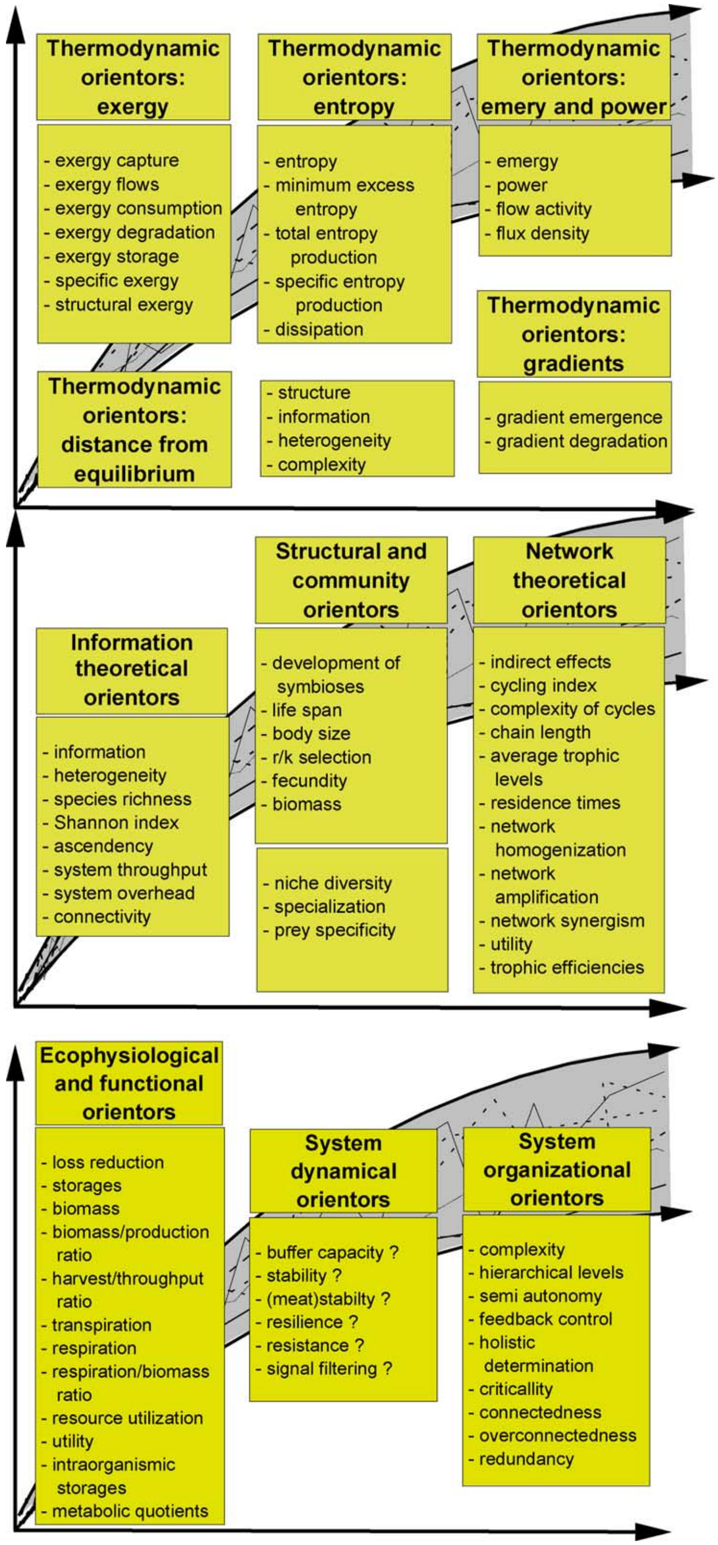
Representing the potentials of ecosystems to provide ecosystem services thus is only possible if both, structures and functions are investigated on an integrative basis. Hence, the utility of ecosystems becomes a matter of ecological organisation.

3. The indicandum: sustainability and ecological integrity

The leading concept of modern environmental management is the global political principle of a sustainable development. It has been discussed in various papers and political statements, and in the essence we are asked to utilise natural resources in a way that enables future generations to take access to these resources at least in a similar mode as applied today.

Taking into account the terms and concepts mentioned in the last chapter, it is possible to use an alternative formulation for the ecological components of sustainable development: ‘‘meet the needs of future generations’’ in this context means ‘‘keep available the ecosystem services on a long-term, intergenerational and a broad scale, intragenerational level’’.

Thus, ecosystem services can be used to construct a systems-based framework for the ecological focus of sustainable development. As we have seen before, the provision of these services results in an appropriate performance of regulation services, and this means that environmental self-organising processes can be viewed as basic ecological requirements for sustainable development strategies: to maintain these services, also the ability for future self-organising processes within the respective system has to be preserved (Kay, 1993). This demand is considered as a focal point of modern environmental management models, such as ecosystem health or ecological integrity. In a recent paper, Barkmann et al. (2001) have defined ecological integrity as a political target for the preservation against non-specific ecological risks that are general disturbances of the self-organising capacity of ecological systems. Thus, the goal should be a support and



Thermodynamic orientors: exergy
- exergy capture
- exergy flows
- exergy consumption
- exergy degradation
- exergy storage
- specific exergy
- structural exergy
Thermodynamic orientors: entropy
- entropy
- minimum excess entropy
- total entropy production
- specific entropy production
- dissipation
Thermodynamic orientors: emery and power
- emergy
- power
- flow activity
- flux density
Thermodynamic orientors: distance from equilibrium
- structure
- information
- heterogeneity
- complexity
Thermodynamic orientors: gradients
- gradient emergence
- gradient degradation
Structural and community orientors
Network theoretical orientors
Information theoretical orientors
- information
- heterogeneity
- species richness
- Shannon index
- ascendency
- system throughput
- system overhead
- connectivity
- development of symbioses
- life span
- body size
- r/k selection
- fecundity
- biomass
- niche diversity
- specialization
- prey specificity
- indirect effects
- cycling index
- complexity of cycles
- chain length
- average trophic levels
- residence times
- network homogenization
- network amplification
- network synergism
- utility
- trophic efficiencies
Ecophysiological and functional orientors
- loss reduction
- storages
- biomass
- biomass/production ratio
- harvest/throughput ratio
- transpiration
- respiration
- respiration/biomass ratio
- resource utilization
- utility
- intraorganismic storages
- metabolic quotients
System dynamical orientors
- buffer capacity ?
- stability ?
- (meat)stabilty ?
- resilience ?
- resistance ?
- signal filtering ?
System organizational orientors
- complexity
- hierarchical levels
- semi autonomy
- feedback control
- holistic determination
- criticallity
- connectedness
- overconnectedness
- redundancy

preservation of those processes and structures, which are essential prerequisites of the ecological ability for self-organisation.

4. The indicator derivation: potentials of self-organisation

To illustrate the path used for the theory-based indicator derivation for ecological integrity, a general ecological principle has to be taken into account. That is the so-called orientor principle (Bossel, 1998; Müller and Leupelt, 1998), a systems-based theory about ecosystem development, which is founded on the general ideas of non-equilibrium thermodynamics (Joergensen, 1992, 2000; Schneider and Kay, 1994) and network development (Fath and Patten, 1998) on the one hand and succession theory on the other (e.g. Odum, 1969; Dierssen, 2000). In the focus of the orientor principle the processes of ecological self-organisation are situated (Müller et al., 1997a,b; Müller and Nielsen, 2000). Self-organised systems are capable of creating macroscopic order from microscopic disorder, thus open systems – such as ecological systems – can produce structures and gradients if they receive a through-flow of exergy (usable energy or the energy fraction of a system which can be transferred into mechanical work, see Joergensen, 1992, 2000). The typical exergy input path into ecosystems is solar radiation. This energy fraction is transformed within metabolic reactions (e.g. respiration, heat export), producing non-convertible energy fractions (entropy), which are exported into the environment of the system. As a result of these energy conversion processes, under certain circumstances gradients (structures) are built up, and maintained. There are two extremal thermodynamic principles which take these conditions into account and which postulate an optimising behaviour of open, biological systems. Joergensen (2000) states that self-organised ecological systems tend to move away from thermodynamic equilibrium, that is build up ordered structures and store the imported exergy within biomass, detritus and information (e.g. genetic information) which can be indicated by structural diversities. In contrast, Schneider and Kay (1994) have stated that the degradation of the applied gradients is a function of self-organised systems, which is optimised throughout their development.

What we have to consider is that both are right: throughout the undisturbed complexifying development of ecosystems – between Holling's exploitation and conservation stages (Holling, 1986; Gundersson and Holling, 2003) – there are certain characteristics which are increasing steadily and slowly. These features are developing towards a certain attractor state which is determined by the specific site conditions and which is a result of the prevailing ecological functions. As the development seems to be regularly oriented towards that attractor basin, the respective state variables are called orientors (Bossel, 2000). Using this ecosystem features as indicators, the naturalness of an ecosystem's development can be depicted. Fig. 1 shows some of these orientors. In general, it can be postulated that throughout an undisturbed development, the complexity of the ecosystems will be increasing asymptotically up to a state, which has been called maturity by Odum (1969). Within this development, exergy storage will be rising, on a materialistic level as well as on a structural basis. With this increasing structural diversity also the diversity of flows and the system's ascendancy (Ulanowicz, 2000) will grow as well as certain network features (Fath and Patten, 2000), and therefore also the energy necessary for the maintenance of the developing system will be increasing. Therefore, exergy storage as well as exergy degradation are typical orientors, and their dynamics can be explained in a contemporary manner. These basic thermodynamic principles have many consequences on other ecosystem features. For instance, the food web will become more and more complex, heterogeneity, species richness and connectedness will be rising and many other attributes, as shown in Fig. 1 will follow a similar trajectory.

What happens if there are disturbances? Especially in the case of high external inputs the orientor values

Fig. 1. Ecological orientors from different theoretical origins. The listed ecosystem features regularly show an optimising behaviour throughout long-term ecosystem development in undisturbed situations. Due to the decreasing adaptivity of ecosystems, which is often correlated with growing complexity, the stability characteristics within the third part of the scheme are exceptions; at least in mature states, they do not function as orientors.

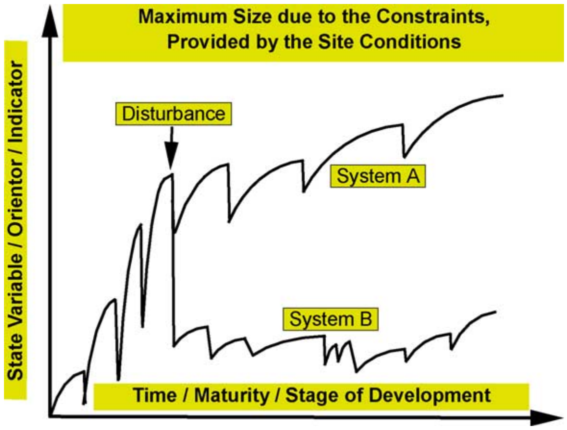


Fig. 2. Reactions of different systems after disturbances. Orientors can be used to depict the resilience of ecosystem features by the degree to which they are able to follow the orientor trajectory after disturbances.

might decrease rapidly. In the following sequence, an adaptive or resilient system will rather soon find the optimisation trajectory again, while a heavily disturbed ecosystem might no more be able to improve the values of the orientors. Therefore, the robustness of ecosystems can be indicated by the orientors as well (see Fig. 2). But we have to be aware of the fact, that high orientor values do not guarantee a high stability or a high buffer capacity. Following Holling's ideas on ecosystem resilience and development, there is a mature stage when complex ecosystems become ''brittle'', when their adaptivity decreases because of the high internal connectedness and when the dynamics of external variables force the system to break down and start another developmental sequence.

5. The indicator set: an aggregate of structural and functional ecosystem features in a developing environment

If we take a close look at the orientors presented in Fig. 1, it becomes obvious that many of them cannot be easily measured or even modelled under usual circumstances. Some orientors can only be calculated on the base of very comprehensive data sets, which are measured on a very small number of sites, only. Other orientors can only be quantified by model applications. Therefore, the selected orientors rather have to be represented by variables, which are accessible by traditional ecological methods of quantification. Thus, the next step of indicator derivation is a ''translation'' of the thermodynamic, organisational, network and information theoretical items into ecosystem analytical variables. Within this step, it has to be reflected that the number of indicators should be reduced as far as possible. Thus, many of the ecosystem variables depicted in Fig. 1 cannot be taken into account. Instead, a small set consisting of the most important items, which can be calculated or measured in many instances is what we have to look for. This set should furthermore be based on the focal variables which are usually investigated in ecosystem research and which can be made accessible in comprehensive monitoring networks. The general sub systems, which should be taken into account to represent ecosystem organisation are listed below as elements of ecosystem orientation:

- *Ecosystem structures*: While ecosystems are evolving, the number of integrated species is regularly increasing steadily and also the abiotic features are becoming more and more complex. This development is accompanied by a rising degree of information, heterogeneity and complexity. Also, specific life forms (symbiosis) and specific types of organisms (r/k strategists, organisms with rising life spans and body masses) become predominant throughout the orienting development.
- *Ecosystem functions*: Due to the increasing number of structural elements, the translocation processes of energy, water and matter are becoming more and more complex, the significance of biological storages is growing as well as the degree of storage in general, and consequently the residence times of the input fractions are increasing. These processes influence the budgets of the respective fractions, which can be measured by input–output analysis. Due to the high degree of mutual adaptation throughout the long developmental time the efficiencies of the single transfer reactions are rising, cycling is optimised, and thus losses of matter are reduced. The respective ecosystem functions are usually investigated within three classes of processes which are interrelated to a very high degree:
  - *Ecosystem energy balance*: Exergy capture (uptake of utilisable energy) is rising during the

undisturbed development, the total system throughput is growing (maximum power principle, see Odum et al., 2000) as well as the articulation of the flows (ascendancy, see Ulanowicz, 2000). Due to the high number of processors and the growing amount of biomass, the energetic demand for maintenance processes and respiration is growing as well (entropy production, see Svirezhev and Steinborn, 2001).

- *Ecosystem water balance*: Throughout the undisturbed development of ecosystems and landscapes, more and more elements have to be provided with water. This means that especially the water flows through the vegetation compartments show a typical orientor behaviour. These fluxes provide another high significance because they demonstrate an important prerequisite for all cycling activities in terrestrial ecosystems. The water uptake by plants, which is regulated by the degree of transpiration.
- *Ecosystem matter balance*: Imported nutrients are transferred within the biotic community with a growing partition throughout undisturbed ecosystem development. Therefore, the biological nutrient fractions are rising as well as the abiotic carbon and nutrient storages, the cycling rate is growing and the efficiencies are being improved. As a result, the loss of nutrients is reduced.

On the base of these items, a general indicator set to describe the ecosystem or landscape state in terrestrial environments, has been derived. It is shown in Table 2.

The basic hypothesis concerning this set is that the demands formulated above (a holistic representation of the degree and the capacity for complexifying ecological processes on the base of an accessible number of indicators) can be fulfilled by these variables. They also represent the basic trends of ecosystem development, thus they show the developmental stage of an ecosystem or a landscape. As a whole this variable set represents the degree of self-organisation in the investigated system. Hence, it can be postulated that (with the exception of mature stages which are in fact very seldom in our cultural landscape) consequently also the potential for future self-organisation can be depicted with this indicator set.

Of course, this parameter set cannot provide a complete indication of sustainability, because the social and economic subsystems are not taken into account (e.g. driving force or response indicators). Also external inputs and other pressures are not represented. But the focal ecological branch of sustainability can be described on the basis of the orientor state indication. In spite of this strategic restriction, the integrity indication provides potential linkages to the human based indicators of the DPSIR scheme. A matrix interrelation with the basic ecosystems services after De Groot (1992) shows that regulation services are well represented in this indicator set and that there are high interrelations with the production services while carrier and information services are not represented in a satisfactory manner (Fig. 3).

Table 2
Proposed indicators to represent the organisational state of ecosystems and landscapes

Orientor group	Indicator	Potential key variable(s)
Biotic structures	Biodiversity	Number of species
Abiotic structures	Biotope heterogeneity	Index of heterogeneity
Energy balance	Exergy capture entropy production entropy production after Svirezhev and Steinborn output by evapotranspiration and respiration	gross or net primary production entropy production after Aoki
	Metabolic efficiency	Respiration per biomass
Water balance	Biotic water flows	Transpiration per evapotranspiration
Matter balance	Nutrient loss storage capacity	Nitrate leaching intrabiotic nitrogen soil organic carbon

The nominated key variables can be regarded as an optimal indicator set. If these parameters are not available other variables may be chosen to reflect the respective indicandum. Doing this, the observer must realise that the quality of the indicator–indicandum relations may be sinking.

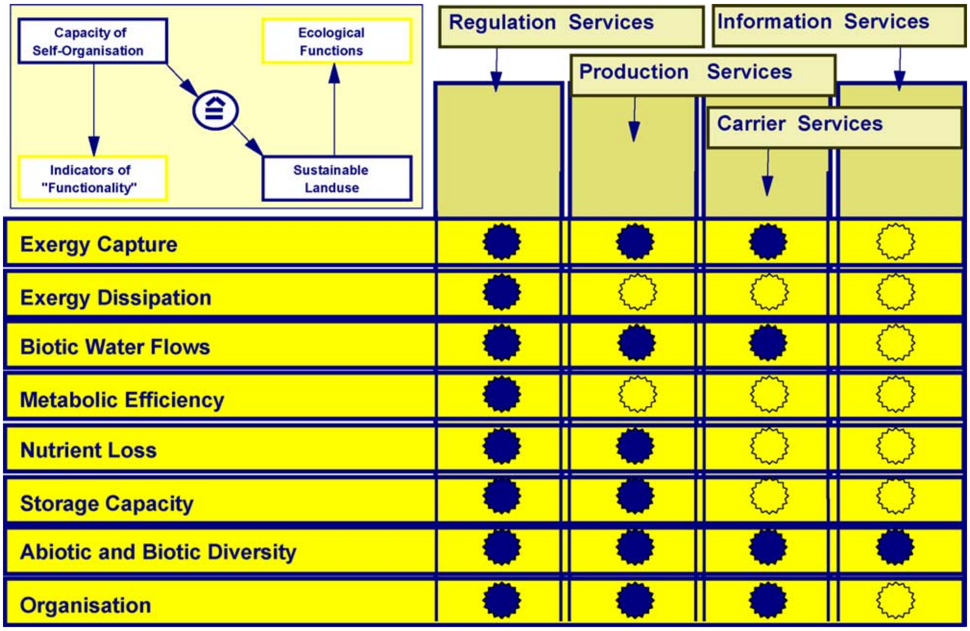


Fig. 3. Interrelations between the proposed indicator set for ecosystem states and four groups of ecosystem services. The matrix shows that there are high correlations between the indicator set and the ecosystemic regulation functions, while, i.e. the representativeness concerning information services is rather small.

6. The applications

This indicator set has been applied within several case studies on several different scales, whereby the linkages between data sources, model outputs and indicator demands have been an object of methodological optimisation throughout the last years. In the following paragraphs, one example will be shown from the ecosystem research project ''Bornhoeved Lakes'' which has been conducted between 1988 and 2001. Within the main research area ''Altekoppel'' comparative empirical ecosystem studies were carried out in agroecosystems and forests (Hörmann et al., 1992). In the following case studies, some results from a 100 years old beach forest and a directly neighbouring arable land ecosystem will be demonstrated. Both ecosystems had a similar agricultural use before the forest was planted. Thus, the question is which ecosystem features and which ranges of the self-organisation capacity have been modified by the different land use schemes (see Baumann, 2001; Kutsch et al., 2001, 1998; Windhorst et al., 2004).

Fig. 4 shows the differences between the two ecosystems with respect to their biocenotic structures. Nearly all investigated organism groups show higher *numbers of species* in the forest ecosystem. One exception is the group of small mammals, who can find very good food conditions in the arable land and who are well-adapted to this ecosystem type. The second structural indicator is the *abiotic heterogeneity*, which was calculated with a GIS based neighbourhood

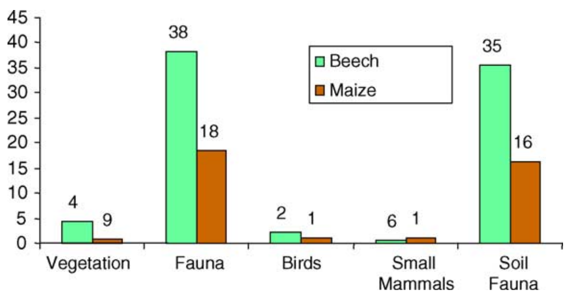


Fig. 4. Comparison of the species numbers in some community groups of the investigated ecosystems; data have been compiled from Hörmann et al. (1992).

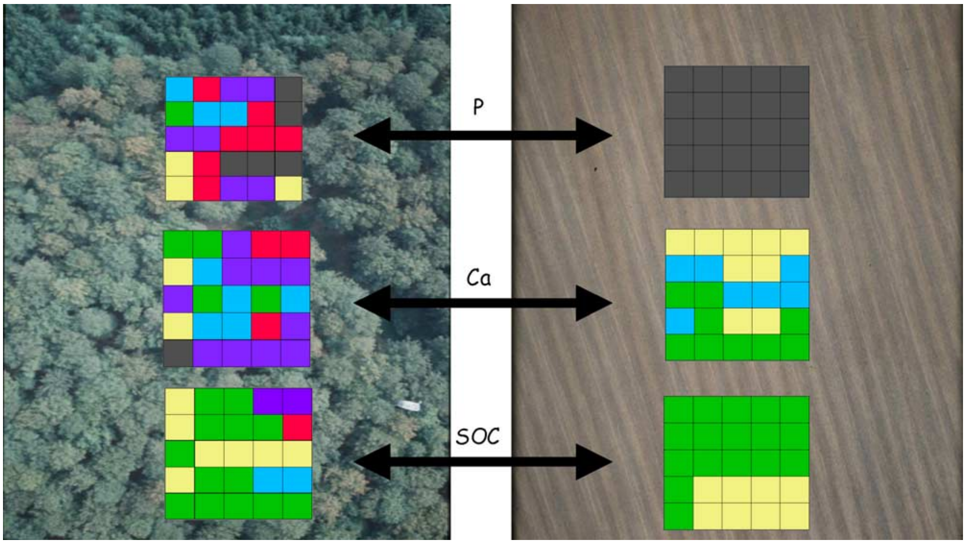


Fig. 5. Abiotic heterogeneity indicators in the investigated forest and the arable land ecosystems in the Bornhoeved Lakes District, data according to Reiche et al. (2001). The contents of phosphorus, calcium and soil organic carbon in the upper soils are mapped for two sub areas of a 10 m × 10 m sampling grid. The data have been distinguished into different classes. It is obvious that in the upper soil horizons of the arable land system there is a much higher homogeneity than in the forest ecosystems. The relationships of the memberships within the grid are 7:1 (P), 6:3 (Ca) and 5:2 (SOM).

method after Reiche (Baumann, 2001). While the index of the forest ecosystem is 0.56 referring to the soil organic matter, the maize field has a value of only 0.08. Also corresponding to the soil chemical constituents H^+, Ca^{2+}, Mg^{2+}, K^+ and phosphate, the forest soil heterogeneity is higher than the respective value on the arable land. Therefore, we can constitute very high differences concerning the structural patterns of these ecosystems. A demonstration of these conditions is shown in Fig. 5. The maps illustrate the heterogeneity of different soil constituents in both ecosystems on the base of a classification in a 10 m × 10 m grid system.

Investigating the *storage capacities* of the two ecosystems, the biomass and the intrabiotic nutrients were used as indicators. The living biomass varied from 131 t C ha^{-1} in the beech forest to 6.5 t C ha^{-1} in the arable land, and the relations for the soil organic carbon is 80 t C ha^{-1} versus 56 t C ha^{-1}, respectively. The correlated ecosystem comparison concerning the *intrabiotic nutrients* is sketched in Fig. 6. It shows that the higher values can be found in the forest ecosystem for both nitrogen and phosphorus compounds.

Another important functional parameter used is the *loss of nutrients*. Fig. 7 shows that there are enormous differences between the two systems. Of course, this is a consequence of the different import and export regimes. But besides these extreme examples, the loss of nutrients seems to be a very general effect, resulting from ecological disturbances. This may be caused by

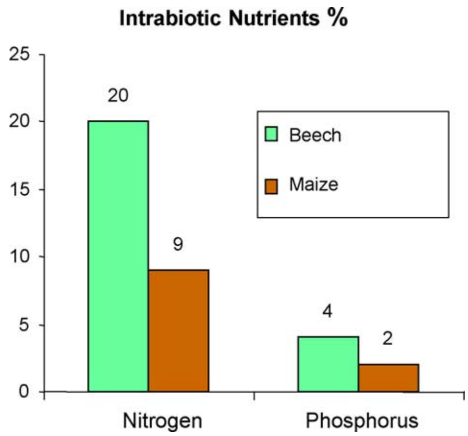


Fig. 6. Comparison of the intrabiotic nutrient contents of the investigated ecosystems; data from Kutsch et al. (1998).

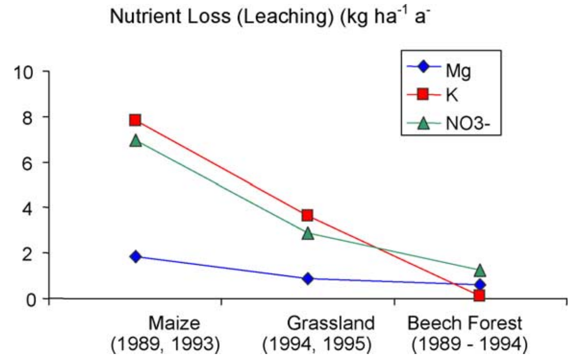


Fig. 7. Comparison of the nutrient loss from the investigated ecosystems; data from H. Wetzel, C.G. Schimming (unpublished). The figure demonstrates that there are significant differences between the ecosystems concerning the leaching quantities of the three chemical compounds.

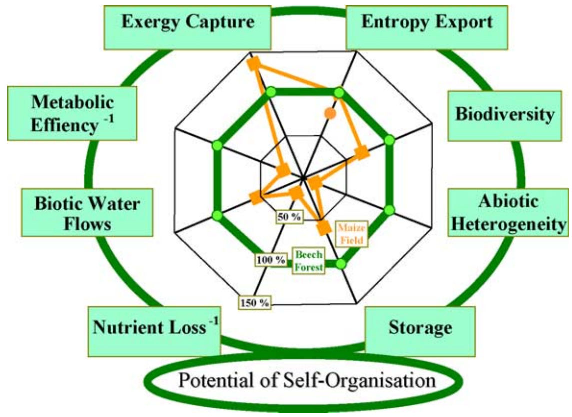


Fig. 8. Synopsis of the indicator values for the two compared ecosystems.

opening the food webs and cycles, which usually become more and more closed in undisturbed developmental phases. Hence, nutrient loss is a suitable candidate for a key indicator of ecosystem health.

Similar results were obtained concerning the *biotic water flows*. The percentage of transpiration from the total evapotranspiration loss was 63% in the case of the forest ecosystem and 34% concerning the field. This signalises the distinct significance of biological flows in the site budgets of water. This item could also be comprehended as an ecosystemic water use efficiency because it is strongly correlated with the capacity of nutrient cycling, and because transpiration is a very important factor of the temperature regulation of ecosystems.

Also, the *metabolic efficiency* (respiration/biomass) of the forest was much higher than the efficiency of the arable land ecosystem. The *entropy production* was calculated in a methodology after Aoki (1998) and on the base of the exergy radiation balance (Steinborn, 2001). While the first method does not produce a satisfying sensitivity, the radiation balance approach can discriminate both ecosystems very well (see Baumann, 2001).

A synopsis of the indicator values is presented in Fig. 8. Looking at the whole figure, it is obvious that all values of the forest ecosystem are higher than the respective numbers of the arable land system with one exception, *exergy capture*. This indicandum has been represented by the gross primary production. The high value on the arable land ecosystem demonstrates that the farmer has been successful in optimising the production of his site. The consequences of this economic orientation can be seen in all other variables: summarizing they show that the degree of self-organisation – and with this the ecological integrity – of the forest is much higher than it is in the field.

While this case study is totally based on small-scaled measured data, additional approaches have been developed on the landscape scale, which can be characterised by a much smaller demand for empirical measurements. To extend the indicator system to the landscape level, it was linked with the GIS coupled modelling system digital landscape analysis and modelling (DILAMO; Reiche, 1996). Using this instrument, many of the explained indicators can be calculated on the landscape scale. The integrated models ''WASMOD'' and ''STOMOD'' have been stepwise enabled to calculate the parameters described in Table 2 in a validated and reliable manner. This methodology has been applied in different areas.

Meyer (2000) used the modelling procedure to foresee the outcome of three landuse scenarios for the whole Bornhöved Lakes District. He could show that especially the nutrient budget indicators show high differences due to distinct land use strategies (see also Reiche and Windhorst, in press). Taking a similar approach, Schrautzer et al. (in press) have derived landscape balances for the different ecosystem types of the Bornhoeved Lakes District, including water, matter and energy budgets for the whole watershed. With this contribution, the methodological linkage between the modelling systems, the GIS and the proposed indicator set has been transferred into a highly applicable form.

The municipality of Plön in Northern Germany was analysed by Barkmann (2001) to show the dynamics of the integrity indicators in different years, using the same methodology. He also demonstrated that especially the loss of nutrient seems to be very sensitive to changes in ecosystem structures and functions. Meyer (2001) has conducted a similar study for two catchments in the biosphere reservation ‘‘Rhön’’ in Central Germany (Schönthaler et al., 2001). Youngest applications were carried out to determine sustainable developmental pathways for reindeer herding in Northern Finland (Burkhard et al., 2003; Burkhard and Müller, in press). Within this study, also economic and social features have been integrated into the analysis. Finally, on a national level the indicator model was used to conceive an indicator system for the National German Environmental-Economic Accounting System together with the Federal Statistical Office (Müller, 1998). One important outcome of this study (Statistisches Bundesamt et al., 2002; Müller et al., 2000) is the idea to implement an ecosystem monitoring system in Germany. But due to many administrative and conceptual problems, this idea will be regrettably realisable in far future only.

7. Discussion and conclusions

With the described concept an indication strategy has been presented which is primarily based on the attempt to apply the general methodologies of ecosystem research in environmental management. The indicators imply a high suitability with respect to ecosystem theoretical considerations and environmental regulation services as focal elements of the ecological sustainability features. Although some improvements concerning single items (e.g. entropy production) are still necessary, the variable set can be used to reflect the basic characteristics of the ecological processes of self-organisation on an interdisciplinary basis, and it is obvious that there are extreme interdepences between the single variables. It has to be clear that in spite of the broad interdisciplinary range, the proposed set of variables can reflect a small portion of the ecological pillar of sustainable development, only. Thus, the focal input of this system can be characterised by the realisation of ecosystemic requirements within a good operational potential. Concluding, we can return to the initial questions of this paper:

(1) Is it possible to represent ecosystem and landscape states on the base of a small number of variables?

    The high number of potential variables, which are measured and modelled in ecosystem research, can be reduced to a small group of aggregated indicators or key indicators if theory-based guidelines are taken into account. Thus, with the proposed concept, an important step of complexity reduction can be gone. There are also attempts for a further reduction (e.g. up to only one key variable), which have not been considered in the presented concept for three reasons. On the one hand, the information loss which is accompanying all steps of aggregation might become too high, on the other the intrinsic reasoning for the causes of certain stages might be lost, and the backside of aggregation procedures, which is a wrong-weighting, internal compensation of different characteristics, implies too many risks for non-sustainable interpretations.

(2) Is it possible to formulate eco-targets for ecosystem and landscape management on the base of ecosystem theories?

    If there is a societal consensus to support the integrity of ecological systems, science can contribute quantitative criteria to measure or estimate the degree of integrity. From the point-of-view of the presented system, this indication includes the developmental state of the ecosystems or landscapes, the general ecological risks and the developmental potential of ecosystems and their compartments. Thus, there is a methodological potential to evaluate holistic ecological features and bridge the conventional mono-disciplinary aspects of sectors, media or other isolated ecological items. Furthermore, the adaptability towards the approach of environmental services provides a potential to depict sustainability on an integrative level. Some recent projects furthermore are working on concepts to transfer the indication from single ecosystems to ecosystem complexes, watersheds, administrative units and landscapes. Concerning that methodological transfer, we are very optimistic to provide a tool box for a model-based and GIS coupled representation of landscape integrity in the future.

(3) Is it possible to derive applicable indicators from applied theoretical considerations?

The last chapter has shown that many respective applications are in work. Consequently, indicator derivation for our comprehension of integrity is possible. It is even proved if the indicator concept might be used as a guideline for new ecosystem monitoring systems in Northern Germany, and in recent studies the indicators have been used to evaluate the outcomes of different planning and management scenarios.

(4) Which problems will arise concerning the indicators' applications?

The methodological and scientific problems around the indicator set will decrease in future as prototypes of a landscape-based version of the modelling systems have been developed and are actually tested, while the acceptance of the concepts will become the focal problem in future. On the one hand, the consciousness of the necessity for holistic approaches is developing rather slowly. And on the other, the fundamental theoretical principles may be too abstract to reach the practicioner's way of thinking. As a consequence, the political and administrative discussions have to be guided into the direction of an acceptance of complexity. These discussions will help to make the barely necessary step to realise the sustainability principle with all of its far reaching consequences.

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