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Ecosystemic Effect Indicators
to assess Effects of Agricultural Land Use on Ecosystems

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>>Die Zeit, die du für deine Rose verloren hast, sie macht deine Rose so wichtig.<<

...

>> Die Menschen haben diese Wahrheit vergessen.<< sagte der Fuchs.

>> Aber du darfst sie nicht vergessen.

Du bist zeitlebens für das verantwortlich, was du dir vertraut gemacht hast.

Du bist für deine Rose verantwortlich...<<

(Aus: Der Kleine Prinz)

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A RECAPITULATING OVERVIEW, RESULTS AND CONCLUSION

1 BACKGROUND AND DEFINITIONS

Agricultural production processes release material (e.g., nutrients, pesticide residues) and non-material emissions into the environment. Physical releases, like pressure, are subsumed as non-material emissions. The emissions influence adjacent ecosystems after transport, transformation and deposition processes. Thus undesired effects in ecosystems may be caused by agricultural land use. Emissions which arrive in ecosystems - after having been transformed - are defined as inputs in this study. The inputs may cause harms on receptors when received in ecosystems. Receptors represent spatial or functional parts of the environment which respond to inputs (Merkle and Kaupenjohann, 2000a).

The connection of both the production system and affected ecosystems (e.g., the agroecosystem itself, lakes or forests) is required as a prerequisite for the assessment of agricultural impacts on the environment. The evaluation of agricultural impacts, however, still remains critical. Firstly, the variety of emissions and inputs occurring aggravates a judgement. The diverse emissions and input properties impair ecosystems in different ways. For instance, toxicity predominately hits the level of species, elements or processes whereas nutrifying inputs affect the level of whole systems by influencing the ecosystem balance. Secondly, spatial and temporal scale transitions complicate the establishment of cause-effect-relationships. When looking at specific emissions one has to deal with time delays in the emergence of effects. Notwithstanding, time has been insufficiently integrated into ecosystemic investigations (von der Wiesche and Werner, 1998). Thirdly, the high complexity of ecosystems with their hierarchically structured organisation enables to quantitatively portray only some representatives of the numerous biotic and abiotic interactions (Mühle and Claus, 1996; van Ittersum and Rabbinge, 1997). Recent assessments of environmental impacts remain restricted to reductive approaches regarding system compartments or specific environmental media (Müller, 1992; Münchhausen and Nieberg, 1997). Consequently, the evaluation of environmental impacts of agriculture still has to be considered as fragmentary. Additionally, loading capacities, threshold, reference, precaution values and ranges of tolerance of receptors serving as a basis for quantitative evaluations are scarcely available.

Indicators have been proposed to serve as a tool solving both the problem of high complexity of ecosystems and the problem of high effort required in taking direct environmental measurements (Bockstaller et al., 1997). Thus, here the hypotheses is formulated that an indicator approach may be the adequate solution for the problem of connecting agricultural production systems and affected ecosystems. Following, the main questions to be answered are:

- Is it possible at all to relate both emissions of production systems and effects in ecosystems by means of indicators?
- How must such indicators look like?
- How to develop the indicators necessitated?
- What importance has to be attached to time dimensions?

The present study shall contribute to the evaluation of sustainable agriculture in Central Europe in interdisciplinary co-operation with other institutes of the University of Hohenheim and the University of Stuttgart. In this context a conceptual model of indicators shall be provided as a basic tool to implement sustainable agriculture.

2 ENVIRONMENTAL INDICATORS AND INDICATOR MODELS

Having decided to choose an indicator approach the next step is a review of the state of the art. As Verbruggen and Kuik (1991) stated, up to now, no practical means for an assessment of the objectives of sustainability exist. This holds true for the agro-environmental domain where the urgent need for evaluation tools is continuously growing (Girardin et al., 1999b). The tools can be provided by means of indicators. A variety of indicator literature is currently available. Several types of indicators, indicator models and indicator frameworks may be distinguished which are discussed in the following.

Since an uniform or standardised indicator definition is lacking at present an own definition is introduced. In the context of the present work an *indicator* is defined as *a measurable variable which characterises systems or system components by reducing complexity and integrating information.*

The current literature shows that indicators are used for different purposes varying from, for example, environmental monitoring to synthesising masses of data. According to the purpose intended, the indicators have to meet specific requirements (Walz and al., 1997). A number of scientific and application features that should be used for selecting indicators is listed in the tables B1 and B2.

The review of the literature ensued a huge amount of indicators for various issues of concern (ecosystem health, sustainability, soil health, environmental monitoring). However, no indicators exist which can be applied in general (Bakkes et al., 1994). The indicators are context dependent, based on concrete objectives and targets. To order the indicators a classification is suggested. The available types of environmental indicators may be divided into two categories (tables B3a and B3b): (1) simple, case- or site-specific indicators with a reductive view and (2) systemic, functional indicators. In the present work the rare systemic indicators are discussed in more detail.

A number of the available indicators form part of an indicator model. Indicator models serve for a definite purpose. Usually, such models aim at an extensive description of relations between economy and ecology (Hoffmann-Kroll et al., 1995). To create purpose depending indicator models the OECD model (OECD, 1993) or related approaches are often taken as a basis. The indicators of indicator models include miscellaneous domains. Basic domains to characterise influences exerted on the environment are pressure, state and response (OECD, 1993) or stress and response indicators (Friend and Rapport, 1991; Rapport and Friend, 1979). These indicator models have in common that they cover scales from regional to global, whereas models for the local scale are rare. Some indicator models like the AMOEBA model (ten Brink, 1991) need reference systems, e.g., a previous natural state or a desired ideal state.

It is shown in this work that indicator models frequently belong to indicator frameworks or indicator systems representing the superstructure behind. The frameworks include societal values and goals, an indicator model with several indicator types and an evaluation system. A framework is required to organise the process of indicator development and selection (Cairns et al., 1993). Furthermore, it should organise individual indicators or indicator sets in a coherent manner.

The question arises from the existence of the numerous indicators and indicator models, how the indicator were derived. Several authors emphasise that there is no defined method to build up indicators (Cairns et al., 1993; Girardin et al., 1999a). However, two principal strategies can be detected: Indicators are either developed by expert judgement/ questionnaires or they are deduced scientifically based.

Many of the indicators are taken of preexistent lists and are selected with little or no modifications (Mitchell et al., 1995). The analysis exposes that the indicators are often presented without specifying the selection process. They are deduced with subjective expert questionnaires. Mitchell et al. (1995) developed a methodological approach to derive indicators for sustainability. However, transparent approaches providing transferable methods to develop systemic indicators for agricultural systems are still lacking (von Wirén-Lehr, 2000, acc.).

Two main strategies are pursued corresponding to the evaluation of environmental degradation at the community or ecosystem level in case that the indicators are deduced scientifically based (Gentile and Slimak, 1992; Munkittrick and McCarty, 1995). Either a bottom-up or a top-down approach is used. Bottom-up, known results of effects in simple systems are transferred to higher more complex systems. Likewise, indicators may be developed bottom-up. In turn, causative agents are determined top-down for an alteration with regard to environmental degradation (Cairns et al., 1993). Accordingly, during the indicator development a goal at a complex level is stepwise broken down. Drawbacks are linked to both procedures: The bottom-up approach may not be goal adequate, whereas the top-down approach is not suitable to solve new problems because it only considers already discovered problems (Zieschank et al., 1993).

A multistage procedure (seven steps) is developed of how to generally identify indicators in the present study (figure B3). The goal definition, serving as general starting point, determines the following methodological steps: The non-measurable principal goal can be broken down into objectives (figure B1) which represent the basis of the indicator derivation. Next, the target group (decision-makers, scientists, farmers etc.) has to be defined because the degree of complex information may be higher if the indicators are intended to be used by specialists for complex goals (Braat, 1991). Subsequently, the indicator building with respect to issues of concern is carried out. Thereby a conceptual model is required. The data needed have to be gathered and potential indicators are compiled. The final indicators are identified in a next step according to the selection criteria. The theoretically deduced indicators are validated in a case study by means of a test of usefulness. To assess the progress towards the objectives the indicators should be quantifiable. Thus they are compared to reference or threshold values. The final step of the procedure is the evaluation of developed indicators by experts.

In summary, the research needs concern

- suitable indicators to analyse ecosystems affected by emissions of agricultural production,
- the synthesis of top-down and bottom-up procedures for the indicator development,
- a comprehensible and transparent method for the indicator derivation of environmental impacts of agriculture.

3 OBJECTIVES

General aim of the study is the provision of a methodological instrument to assess effects on ecosystems resulting from agricultural production processes by linking both the production system and the affected ecosystem. For this purpose an indicator approach is chosen. Figure A1 shows an overview of the single investigations of the study.

The examination of existing literature concerning environmental indicators, indicator models and frameworks (part B) provides an overview on the state of the art. The critical review of available indicators reveals that neither appropriate types of indicators to link both production systems and ecosystems nor comprehensible methods for the deduction of indicators are currently available. It is concluded from the results of the review (part B) that an essential task is to develop a plausible, transparent and comprehensible method to derive suitable indicators (part C).

To illustrate and possibly improve the developed methodological procedure the applicability is tested with regard to material- and non-material inputs in a case study (parts D and E). The case study especially focuses on the agroecosystem itself as affected ecosystem. An assessment of environmental impacts of agricultural production remains difficult because of the manifold types of emissions, pathways and inputs occurring. To reduce the amount of parameters to be assessed and to involve the determining variables the effective parameters must be identified. Consequently, a classification of emissions and inputs as a prerequisite for a reasonable derivation of indicators is performed (appendix, tables X1 and X2). The yielded indicators are as far as possible related to threshold values for a final quantitative evaluation.

The implementation in the case study demonstrates the significance of time dimensions. Testing the non-material input of soil pressure (part D) already shows that spatial variations as well as temporal aspects, e.g., system reversibility/recovery, represent essential issues to be considered. Thus a special focus of the test for material inputs is laid on temporal dimensions of emissions, effects and depending indicators (part E).

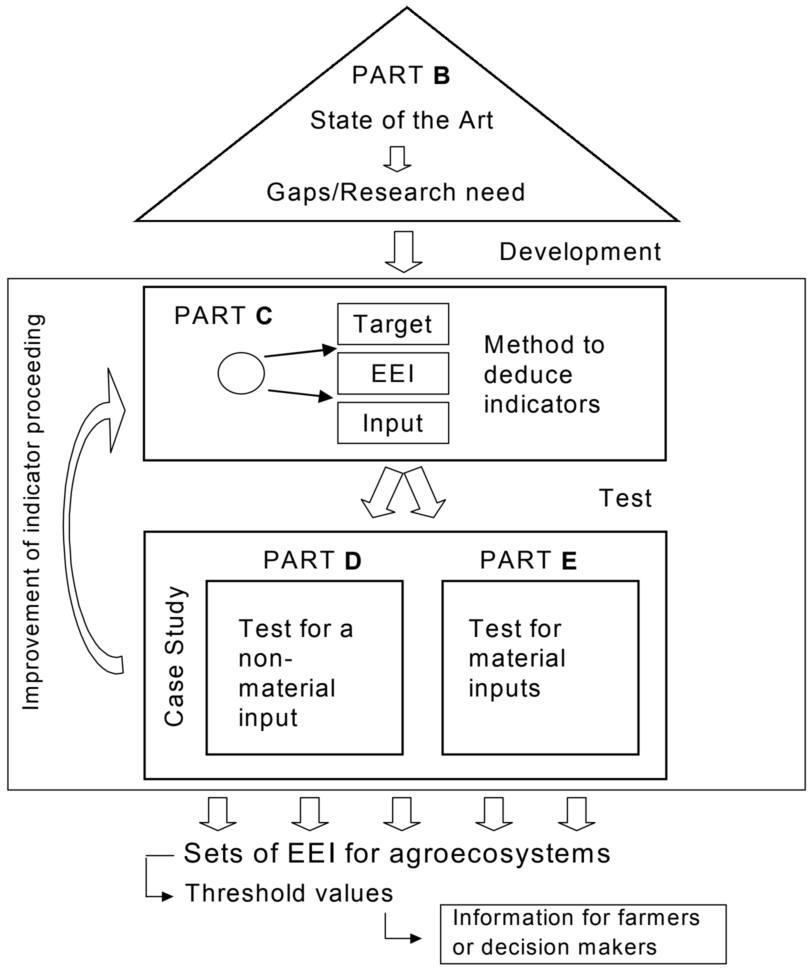

Figure A1: Overview about the single investigations which were carried out (EEI: Ecosystemic effect indicator. The capital letters relate to the single chapters of the present study)

Having presented the results of the state of the art (part A2), main results and conclusions of the work are summarised in the following sections. Details can be gathered from the paper manuscripts of the parts B to E.

4 DERIVATION OF ECOSYSTEMIC EFFECT INDICATORS

The study aims at the development of a transparent and comprehensible method to provide indicators. The following frame conditions have been set:

(1) A method has to be created not limited to a concrete landscape or site. Consequently, a deductive proceeding is not feasible. Hence a function based approach is performed.

(2) The target groups of the indicators intended represent the scientific community as well as planners.

(3) The methodological approach has to start at determined targets and objectives. The utility functions of ecosystems represent the target in this study. Such functions comprise the regulation (filter, buffer, transformation), production, habitat and storage function (de Groot, 1992; Fränzle et al., 1993). In managed landscapes, however, the protection of functions is insufficient. Thus an assignment of targets and values to functions is necessitated (Doppler, 2000 i.p.).

Depending on the targets and objectives the indicator requirements were established (cf. table B1 and B2). The indicators destined to link emissions of agricultural production and effects in ecosystems must be meaningful for the maintenance of ecosystem functioning as well as sensitive for the impacting inputs. Furthermore, the indicators have to be integrative, methodologically transparent and desirably functionally linked to the sources of impacts. Finally, the availability of data remains a main constraint that determines the whole indicator development.

In the present work I propose ecosystemic effect indicators as a new type of indicators. According to the requirements these indicators are defined as follows: >>*Ecosystemic effect indicators represent receptors sensitive to material and non-material inputs. They indicate the functioning of ecosystems*<< (part C).

One essential feature for the development consists in a combination of top-down and bottom-up procedures (figure C1). This strategy enables to derive indicators which generate a cause-effect relation – independent of the hierarchical level of the ecosystem the indicators are identified on.

Since the ecosystem functioning has to be maintained, the indicator derivation is based on utility functions on the one hand. On the other hand the derivation is based on agricultural measures and their specific inputs in an affected ecosystem. The suggested approach relates both the ecosystem and the emissions of the agricultural system.

In the first step a compilation of characteristics for the diverse utility functions (appendix, tables X3 – X12) is performed top-down. Ecosystems may be characterised by the hierarchical order of superior relations and properties of subsystems located on level II (e.g., food-webs) (figure A2). These superior relations and properties may be subdivided into subsystems located on level I (e.g., primary producers). The subsystems can be split into elements (e.g., earthworms) or single processes (e.g., respiration) located on level 0 (Doppler, 2000 i.p.).

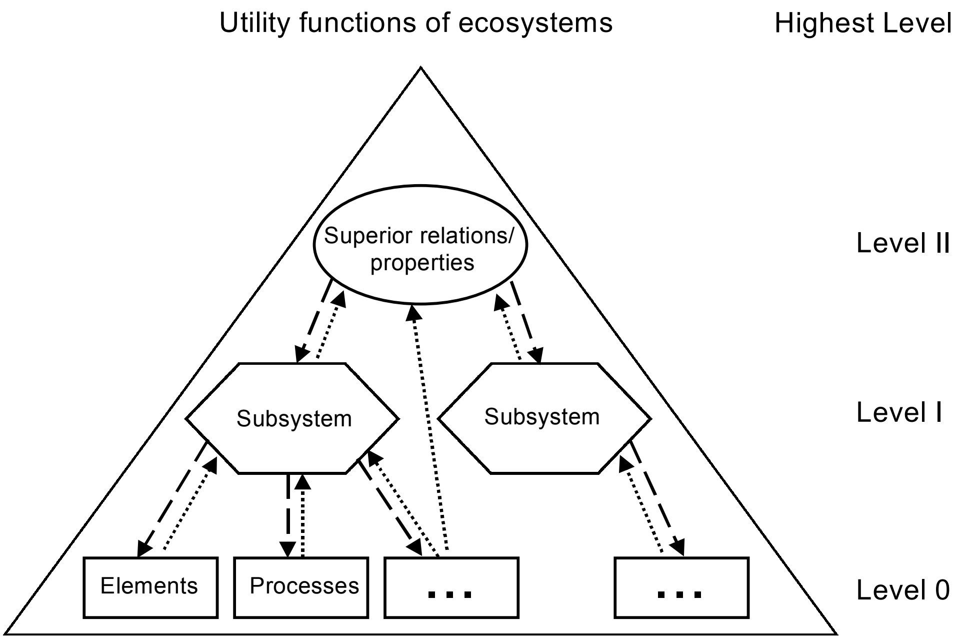

Figure A2: The diverse hierarchical levels of ecosystems and their interactions. Higher system levels control lower ones. In turn, the potential of higher ones is restricted by the behaviour of the lower. Lower levels may also directly influence higher ones

Next step is to look at one specific input. A list of observable biotic and abiotic receptors and probable effects is compiled bottom-up for this input (appendix, tables X13 – X20). The receptors represent potential effect indicators for the input considered.

Finally, the lists with characteristics of the selected utility function and the list of potential effect indicators for a specific input are overlapped and intersections are identified with assistance of expert knowledge. The result is a selection of ecosystemic effect indicators for the utility function regarded and the input chosen. The procedure has to be conducted for each function under consideration and for each input of interest. In this way one yields sets of ecosystemic effect indicators for the ecosystem under investigation (appendix, table X21).

The goal set and the requirements properly specified simplify the selection of suitable ecosystemic effect indicators. Time is recognised as an additional aspect in this work which may not be ignored in facilitating the indicator selection. It is proposed to arrange the temporal heterogeneity of receptors' sensitivities as well as the dynamics of inputs occurring and to look for intersections on similar temporal scales.

As advantage of the procedure corroborates that it is not site-specific and can be applied to various ecosystems. However, the implementation will have diverse expressions at each natural site. Therefore, the application requires that certain parameters are known. In a next step, the method newly developed and its applicability have to be tested with regard to its operativeness in a case study.

5 APPLICABILITY OF ECOSYSTEMIC EFFECT INDICATORS: NON-MATERIAL INPUT

The developed method was tested in an exemplary case study. At first, an agroecosystem as directly affected ecosystem and the soil pressure as a non-material emission were examined. The data used in the case study were gathered in the "Sonderforschungsbereich No. 183" in the Kraichgau-Region, Germany (Lorenz, 1992; Zeddies, 1995). The production and utilisation of energy crops was taken as an example. To examine energy crops provides the advantage of a clear cut frame with a well defined production and utilisation system besides the topicality of energy crops with regard to sustainability. An exemplary cultivation procedure for Triticale to be used as biofuel for a distinct heat provision supplied the emission and the respective input data.

The focus of this work is laid on the emission of soil pressure during the tilling steps (table D1) and its effects in an agroecosystem. Various undesired side effects of agriculture were extensively examined in literature, e.g., acidification or pollution, whereas soil degradation was less studied. The spatial extension of the emission predominately appears as banded impact. Soil pressure represents an input periodically emerging which strongly depends on the pressure and duration of the mechanical loading of the machinery used. This input causes short-term (regarding plough layer compaction) as well as long-term (regarding subsoil compaction) effects of mainly local significance.

As the first step of the indicator derivation procedure the characterisation of the utility functions was carried out. Done for the first time the compilation is extensive. Nevertheless, once compiled it provides the advantage to be subsequently utilised for the development of ecosystemic effect indicators concerning other inputs. For each utility function the describing characteristics were compiled top-down (appendix, tables X3 - X12, examples depicted in table D2). The examination ensued that such characteristics may not always be facile assigned to the diverse levels due to complexity.

Here, the habitat function will be exemplary focused. Food networks as a relation of level II belong to the habitat function. They can be split up into characteristics like consumers, producers, predator-prey-ratios etc. on level I. The characteristics of level I are further broken down into air-filled porosity, water-filled porosity, macro-porosity, individuals of earthworms etc.

The effects possibly occurring and the receptors were compiled bottom-up in the second step. Generally, inputs cause various effects on different hierarchical levels (figure E1). The present study demonstrates the manifold unfavourable consequences of soil pressure (table D3, X13). Conceivable effects of the input soil pressure predominately influence characteristics of level 0 and I. Soil pressure strongly affects the pore spectrum, macro porosity, air-filled porosity, penetration resistance etc. which are meaningful for the subsystem of porosity. In turn, the soil structure, aeration and the nutrient cycling which represent essential characteristics for the habitat function may be impaired on the level II. Beyond, soil pressure affects other receptors and a number of other effects occurs (appendix, table X13 and X14).

Considering soil pressure distinctly indicates the importance of noting temporal features. The hypotheses underlying this issue are (1) The subsoil impairment is of higher relevance because it is regarded as being persistent. (2) Without an interruption of cultivation, there remains not enough time for the system to regenerate. (3) Moreover, reversibility of effects is rarely observed.

The habitat, filter, buffer, transformation, storage and production function have been defined as utility functions characterising the affected agroecosystem. By overlapping the lists of characteristics for the utility functions (compiled top-down) and the list with potential effect indicators for soil pressure (compiled bottom-up) a set of ecosystemic effect indicators is yielded (table D4). Macro porosity is found as an ecosystemic effect indicator for the habitat function. Representative ecosystemic effect indicators for the transformation function are the respiratory intensity and the metabolic quotient. The intersection of the lists of characteristics and potential effect indicators ensues the pore spectrum, above all the pore volume between 1 and 100µm as ecosystemic effect indicator for the filter function. The field capacity is detected as ecosystemic effect indicator for the storage function (concerning water), and the penetration resistance or the macro porosity are ecosystemic effect indicators for the production function.

In some cases the deduction of ecosystemic effect indicators proves to be limited. Firstly, antagonistic effects aggravate the determination of a decisive indicator. Secondly, if an input predominately influences non-chemical characteristics the development of an ecosystemic effect indicator for a chemically determined function may be restricted. Thus a direct ecosystemic effect indicator could not be identified for the buffer function with regard to the mechanical input of soil pressure.

The developed ecosystemic effect indicators were related to threshold or reference values as far as available in literature (table D5). Existing threshold values permit to maintain certain characteristics of ecosystem functioning. These values may be opposed to technically permitted limits. For instance, Horn (1999) argued that contact pressures of 50 kPa and axle loads of 2,5 t already entail irreversible deformation of silty soils in humid spring. Other recommendations were that the loads on single axle units should not exceed 6 t (Danfors, 1994). It has to be taken into account, however, that usually threshold values cannot be directly derived from existent data. The setting of thresholds is subjected to considerable uncertainty and frequently reflects decisions on the basis of value judgements. Further a relation to thresholds is restricted through a deficiency of limits in current research.

The present work elucidates that an application of the indicator derivation procedure for non-material input succeeds. To be applied by farmers the information of ecosystemic effect indicators must be transferred into decision aid tools. Developing such decision aid tools requires a consideration of external factors, e.g., moisture, site properties, machinery used etc. Finally, these decision aid recommendations may be qualitative ones, e.g., the use of another machinery on a silty soil. Quantitative ones may also result, e.g., a soil moisture content that must be at a specific state before tilling.

6 APPLICABILITY OF ECOSYSTEMIC EFFECT INDICATORS: MATERIAL INPUTS

Having successfully applied the method to derive ecosystemic effect indicators for a non-material input as a next step the method was tested for material inputs with a special focus on temporal features. Part A5 already stressed that time is of high relevance. Two reasons to turn the attention on time dimensions appear: Firstly, in contrast to space time is incommensurable systematically dealt with in actual impact assessment (von der Wiesche and Werner, 1998) but plays an important role. Secondly, the sustainability background requires the observation of short-term as well as long-term consequences of impacts. Short-term considerations of acute effects are often carried out whereas long-term assessments with a focus on accumulation and chronic effects are rarely performed.

As for the non-material example the data used were based on the example of a cultivation procedure for Triticale in the Kraichgau-Region. The production and utilisation of, e.g., Triticale revealed a big amount of data for emissions and inputs. To handle this variety a classification and categorisation of substances separated into emissions and inputs was performed (appendix, tables X1 and X2). Criteria used were scope and scale (Scheringer, 1999). The proceeding to estimate the relevant substances simplifies the following derivation of ecosystemic effect indicators. Consequently, it is not necessary to deduce ecosystemic effect indicators for all imaginably occurring emissions. The classification of emissions and inputs (table E1; appendix, table X1 and X2) served to decide which material emissions and inputs to take for a detailed examination in the present study.

Scope criteria for the selection of relevant emissions depicted the persistence, toxicity and frequency of use of the substances applied. The fungicide carbendazim and the heavy metal cadmium contained in phosphate fertilisers were pre-selected as potential stressors. Carbendazim is frequently applied against fungal diseases in wheat. In general, the stability of carbendazim does not exceed one year (Perkow and Ploss, 1999). Carbendazim has been identified as a chemical stressor for the soil fauna (Förster et al., 1996; Römbke and Federschmidt, 1995). A special interest is laid on heavy metals because of their inherent persistence. Phosphate fertilisers usually comprise amounts of heavy metal contaminants derived from the phosphate rock. Thus phosphate applications involve regular cadmium additions (Wilcke and Döhler, 1995). Cadmium tends to accumulate in the surface soil over time thereby potentially disturbing soil ecosystems and even influencing human health.

Concerning the first step of the indicator derivation procedure the characterisation of the utility functions was taken from the results yielded in part D (table D2; appendix, tables X3 – X12).

A worst case scenario was assumed in the present investigation where the whole amount of active substance applied attains the soil surface. The focus of effects with respect to time aspects should be the short-term scale for carbendazim. An effect may be immediately initiated or at least occurring within one year (Domsch, 1992; Perkow and Ploss, 1999). The effects of carbendazim are characterised through a selective impact on determined receptors (table E4; appendix, table X15 and X16). Effects on unspecific soil biological parameters could not be proved. The table E4 portrays potential effect indicators for the input of carbendazim.

In turn, for cadmium the focus on the middle- and long-term scale is required. Cadmium may affect certain receptors on a short-term scale, e.g., a population of microorganisms.

More frequent, however, are effects on a larger time scale because cadmium tends to accumulate in soil. This may entail harmful effects after having reached a risky concentration. A broad spectrum of effects due to cadmium is listed (table E3; appendix, table X17 and 18). The receptors include plants, microorganisms, the macrofauna and even humans. However, the effects often depend on soil properties.

A variety of feasible combinations for the ecosystemic effect indicators results from the characteristics of the utility functions on the one hand and the potential effect indicators on the other hand. The integration of time aspects simplifies the selection of a representative ecosystemic effect indicator for cadmium and carbendazim. It is necessary to look for intersections between the time frame of stress impact and the process sequence or sensitivity of the receptors with respect to time dependence. The farmer applies carbendazim in spring when several of the receptors, e.g., earthworms are highly sensitive because their reproduction takes place (figure E4). Consequently, the number of juvenile earthworms is yielded as a ecosystemic effect indicator regarding the input carbendazim and the habitat function.

The inputs of cadmium and carbendazim primarily cause biological and chemical effects. Therefore, direct ecosystemic effect indicator could not be yielded for the filter function which represents a physically dominated utility function. The number of macropores might be an indirect indicator for carbendazim with regard to the filter function. Identified ecosystemic effect indicators for the inputs of carbendazim and cadmium in the present study can be gathered from the table E5.

The test of the indicator derivation method for material inputs improved the supposition that the inclusion of temporal aspects for a simplification of the indicator selection is useful. On the one hand the consideration of temporal dimensions is important with regard to time and frequency of stress occurrence and duration. On the other hand the test for material inputs demonstrates the relevance of attending the alterations in sensitivity of receptors. This refines the approach to deduce ecosystemic effect indicators. Since many impact examinations focus on short-term effects in current research, however, limitations may appear.

7 ECOSYSTEMIC EFFECT INDICATORS: A TOOL FOR ASSESSING ANTHROPOGENIC IMPACTS ON ECOSYSTEMS WITHIN THE FRAME OF SUSTAINABLE AGRICULTURE?

When considering impacts of agricultural land use on ecosystems one has to deal with manifold emissions and subsequent inputs. The complexity of hierarchical, temporal and spatial scales aggravates a judgement. An indicator approach can be taken as a suitable proceeding to reduce the complexity. In the present study a classification of emissions and inputs was proposed and performed that supplies a fundament to judge their relevance as one starting point of the developed indicator derivation procedure. Quantitative as well as qualitative estimations are provided as a prerequisite to deduce appropriate indicators.

The interpretation of existing indicators revealed that the task is characterised by two main types of available indicators disposable. Nevertheless, the following drawbacks appear: Firstly, current research provides simple case- or site-specific indicators. Such indicators are restricted to the problem they were deduced for and are not transferable to other problems or sites. A critical analysis demonstrated that these indicators are not suited to the purpose of a systemic approach to link emissions of agricultural land use and effects in ecosystems not located in a specific landscape. Further existing are systemic indicators, however, also inappropriate for the purpose intended. Secondly, it was pointed out that scientifically based strategies to develop indicators are accessible (Cairns et al., 1993). Transparent approaches providing transferable methods to deduce systemic indicators, however, are lacking. Existing approaches with other goals have not yet been transferred to agricultural production.

A comprehensible method to derive systemic indicators was successfully developed and critically tested in this work. An analysis and compilation of system key functions or elements provides the basis to develop a site-independent indicator derivation strategy. A model-based derivation of indicators enables to deduce indicator sets suitable to describe the condition of diverse systems referring to the dynamic and systemic aspects of sustainability. The method developed in the present study is featured by a transparent argumentation. Overlapping the characteristics derived top-down and the potential effect indicators compiled bottom-up stands out by a comprehensible proceeding. Nevertheless, the selection of final ecosystemic effect indicators with expert knowledge implies a certain subjectivity influenced by the question posed, the goal determined, the site examined and the priority set by the experts.

A further question remains: how to extrapolate effects on a low hierarchical level to consequences on higher levels? As figure E1 demonstrates impacts not always trace from one level to another. They can directly impair higher levels. The performed characterisation of utility functions (top-down; appendix, tables X3 – X12) allows for a precise analysis which characteristics are essential for a specific function on the one hand. On the other hand the compilation of potential effect indicators (bottom-up; appendix, tables X13 - X20) permits to check the characteristics directly impaired or indirectly influenced. Thus the indicators identified correspond to the different hierarchical levels.

Already cited in literature are indicators for the whole functioning as well as for subsystem functions (Rapport, 1998). Or, indicators exist for endpoints of impacts. The ecosystemic effect indicators go beyond existing indicators in so far as they integrate a reference to the functioning of ecosystems and not only indicate effects.

The case study illustrated the applicability of the indicator derivation method for varying inputs. Testing the approach for the non-material input elucidated the motivation of indicator selection (part D). The case study showed that no indicator can be derived if an input does not significantly impair the utility function under consideration with regard to the selection of the ecosystemic effect indicators. Beyond, if the impacts cause antagonistic effects it will scarcely be possible to detect an ecosystemic effect indicator.

The implementation of the methodological approach for the example of toxic substances revealed that careful attention should be paid to the temporal issue (part E). The input cadmium is an impact inducing main effects on a long-term scale because of accumulating over time in the soil ecosystem. Regarding time features the monitoring aspect to follow a development of disturbances over time represents an essential issue. Ecosystemic effect indicators predominately have another intention but they additionally permit to monitor long-term effects of agricultural land use by periodically checking the indicators identified at a specific site.

Ecosystemic effect indicators aim at the target group of the scientific community as well as planners. The ecosystemic effect indicators are found as described above for the problem of assessing agricultural impacts on ecosystems. Depending on the main focus a selection of other indicators according to the tables X13 – X20 (appendix) is conceivable. The approach including the tables provided in the appendix supports planners to develop ecosystemic effect indicators according to their specific problem/goal and site.

The ecosystemic effect indicators do not address farmers. Farmers need other information. They cannot measure, e.g., macro-porosity in field. This requires a transfer of the ecosystemic information to the production part in form of decision aid tools. In some cases direct recommendations may be deduced from the ecosystemic effect indicators, e.g., to apply Thomas phosphate containing less cadmium instead of Triple superphosphate, that allows farmers to maintain the sustainability of their agroecosystem. Hence they are enabled to efficiently produce on a long-term scale.

Despite the advantages of the developed indicator derivation procedure one significant constraint restricts a final sustainability assessment. To quantitatively evaluate impacts of agricultural land use necessitates threshold values or limits. At least, reference or tolerance values are required. Therefore, the ecosystemic effect indicators are brought into relation to threshold values. However, these quantitative data for an assessment are rarely available or not yet explored. Frequently, the databases comprise data derived from toxicity tests, e.g., NOEC or LC values which can be hardly applied to field conditions. As far as available the threshold values belong to respective scales (Doppler and Böcker, 1999). If existent, the threshold values were frequently developed on the level of elements (cf. appendix, table X22). In a reductionistic way, however, a systemic synthesis is aspired.

The identification of ecosystemic effect indicators according to the method suggested may make the determination of threshold values more effective. To which level a substance input, e.g., carbendazim, may be tolerated by an affected ecosystem is decided based on the indicator most sensitive for this input and significant for the ecosystem functioning.

A restriction may also occur through difficulties in specifically assigning effects to inputs. As one reason interactions may impede exact cause-effect-relationships. For instance, the addition of zinc lessens the plant uptake of cadmium (Grant et al., 1998; McLaughlin et al., 1995). Also time delays appearing between the release of an emission and effect occurrence may hinder an assignment. This coincides with effects for whom the initiator may not be unambiguously determined. In some cases, the indicator selection may be aggravated by the aspect that the potential indicator is meaningful for the input considered but does not fit very well to a specific utility function.

The present work treated effects appearing on the on-site scale. In implementing the indicator approach for adjacent ecosystems on larger scales to assess off-site effects one has to deal with the transport problem which is not yet adequately resolved. Effects in ecosystems spatially away from the agroecosystem allow neither quantitatively nor qualitatively to precisely trace cause-effect relations. The gap between site of emission and site of effect is characterised by diverse spatial and temporal scale transitions where complex transport and transformation processes occur.

8 CONCLUSIONS

Ecosystemic effect indicators prove to be a promising tool for an assessment of anthropogenic impacts on ecosystems. To conclude the questions posed (part 1: background) may be answered as follows:

The interpretation of current literature reveals that both simple or systemic environmental indicators provided in literature are not suitable for the integrative approach intended in this work. Therefore, the new type of ecosystemic effect indicators embedded in an indicator model on the ecosystem scale (local and regional) is developed.

Seven steps necessary to generally build up indicators are exposed in the present study including a clear method to derive the ecosystemic effect indicators which are function oriented. The complexity of relations between agricultural emissions and effects in ecosystems requires an optimal methodological integration of requirements and selection criteria for the indicators concerning scientific as well as application features. By combining top-down and bottom-up strategies the indicator derivation method is developed. The utility functions of ecosystems on the one hand and the inputs of agricultural production on the other hand represent the starting points of the approach.

Results of the case study demonstrate the applicability of the developed indicator derivation method for the on-site scale. The example of the input of soil pressure shows that the indicators may fairly well be related to threshold values allowing for quantitative statements. In many cases, however, such quantitative threshold limits are lacking, consequently restricting a final quantitative assessment of impacts of agricultural production on ecosystems.

It ensues from the application of the indicator derivation method for material inputs that great importance has to be paid to time aspects. On the one hand the frequency and duration (and potential accumulation) of impacting stress and on the other hand the temporal sensitivity of receptors are concerned. Integrating temporal aspects into the consideration simplifies to select the ecosystemic effect indicator appropriate for a specific input.

The present study shows the successful linkage of agricultural emissions and effects in ecosystems for the on-site scale. When implementing the indicator derivation method in adjacent ecosystems difficulties will appear in establishing quantitative cause-effect relations.

As main foci of future research are proposed:

(1) The application of the approach to derive ecosystemic effect indicators for adjacent affected ecosystems where the temporal and spatial scale transitions become significant. A suitable subject would be an affected aquatic ecosystem where momentous influences are expected by the emissions of nitrogen and phosphate. This impairment particularly concerns the system balance. Nutrification and acidification represent effects predominately influencing the system level whereas toxic substances like pesticides or heavy metals affect the species or population level. The application of the method to deduce ecosystemic effect indicators would conceivably succeed for an aquatic ecosystem. Opposed to the on-site scale different statements are expected concerning causality where relations might be more imprecise and loading capacities where more qualitative statements might result.

(2) Further, the research should be forced in methods reasonably aggregating indicators to reduce the effort in considering large numbers of indicators.

(3) Another useful field would be the transformation of ecosystemic effect indicators into decision aid tools which may directly be implemented by farmers.

Ultimately, regarding the discussion of limits the collaboration with social scientists is necessarily required. Transparency is needed in providing scientific fundamentals. As society sets preferences and priorities the precaution principle is postulated with regard to sustainability assessments.

The political decision makers define limits. To pave the way such threshold limits should be scientifically preferably based.

B STATE OF THE ART OF ENVIRONMENTAL INDICATORS – USABILITY FOR THE DERIVATION OF ECOSYSTEMIC EFFECT INDICATORS

ABSTRACT

Environmental indicators are gaining more and more attention. They represent powerful tools which address different issues of concern. This paper reviews the state of the art of methods for indicator building, the various types of environmental indicators, how to classify them, the indicator models and their underlying frameworks. The options and limitations of environmental indicators are analysed with respect to their applicability in assessing the effects of agricultural production processes upon ecosystems. On the basis of this analysis we outline an approach for the derivation of ecosystemic effect indicators. Most papers considered address the issues of sustainability/sustainable development, ecosystem health/integrity and environmental monitoring. Currently, methods for the development of indicators are often unclear and non-transparent. Existing conceptual approaches to indicators show a high diversity with regard to their methodological (e.g., derivation procedure) and theoretical (e.g., goals) elements as well as their applicability. Our analysis ensued a lack of suitable systemic, function-oriented indicators that can be applied to assess the effects of agricultural production on affected ecosystems. We propose a fundamental seven step strategy to build indicators in the current study. The elaboration of these steps is mainly determined by the first step where goals and objectives are defined, including the definition of the target groups. As a result of our consideration we advocate a modified indicator model, a new type of indicator and a method for its derivation.

INTRODUCTION

Impacts of human activities on the environment are growing. Such impacts have to be assessed systemically, especially against the background of sustainability. Sustainability is an important and relevant political issue. Beginning at the conference of the United Nations in Rio de Janeiro 1992 and based on the Brundtland Report (WCED, 1987), the idea of sustainable development is a central goal of societal development and will increasingly influence future policies. Sustainable development touches various domains.

Besides ecological aspects, economic and social aspects are also implied. The concept of sustainability is rather political than scientific (ten Brink, 1991). Because of the mainly abstract and theoretical character of sustainable development, the implementation still remains critical. As Verbruggen and Kuik (1991) stated “although sustainable development has become a key concept, practical means to evaluate an initiative in relation to the objectives of sustainability do not exist”.

The need for an integrated systemic framework (Waltner-Toews, 1996) and evaluation tools with regard to environmental effects is growing, particularly for sustainable agriculture. Recent sustainability assessments of agricultural systems have to be considered limited, since they are based on simplifications and normative settings of boundaries that reflect, and subsequently assess, only parts of the current situation (von Wirén-Lehr, 2000, i.p.). In most cases the research was sectorally carried out, concentrating on compartments or specific environmental media (Müller, 1992). Consequently, the evaluation of environmental impacts of agriculture (especially on ecosystems) still is fragmentary. Moreover, ecosystems are highly complex that complicates an exact determination of their limits and regeneration rates. Additionally, due to the lack of empirical data only few of the numerous diverse biotic and abiotic interactions and interdependencies can quantitatively be portrayed (Mühle and Claus, 1996; van Ittersum and Rabbinge, 1997).

There are global efforts to quantify and assess the influences of agricultural production on the environment in order to draw conclusions for agricultural and environmental policy. Agricultural production and utilisation of goods, e.g., processing of products or combustion in heating plants have outputs that are material (e.g., pesticides) and non-material (e.g., soil pressure). The outputs are transported and transformed as a function of space and time. The resulting concentration and deposition (inputs) may have significant impacts and may cause complex effects upon the environment at different scales. This concerns both the environmental abiotic (soil, air, water) and biotic (species, communities) resources.

Environmental indicators are increasingly employed to assess the environmental impacts of various anthropogenic stresses on ecosystems. They have been proposed as a tool to solve the problem of high complexity of ecosystems as well as to reduce the amount of effort put into taking direct measurements and determining limits (Bockstaller et al., 1997).

Indicators are not only a medium to reduce complexity they also serve as an auxiliary means for evaluation purposes. Thus they may play a role in the implementation of sustainability.

Our current study is part of an interdisciplinary project on sustainability in agriculture, titled "Sustainable Production and Utilisation of Energy Crops" (SPUEC) with focal points on consequences of crop production and utilisation systems in Central Europe. The project focuses on the ecological aspect of sustainability as have Hansen and Oestergard (1996). We regard the life cycle of crops as being ecologically sustainable if none of the ecosystems affected (either the agroecosystem itself or others, e.g., aquatic ecosystems or forests) and its components is impaired in the long run (Härdtlein et al., 1998). The basic aim of our integrated approach is to develop a tool that relates the production systems to affected ecosystems considering the entire system. Therefore, we are in need of systemic, transferable environmental indicators.

Indicator derivation turns out to be a critical issue. A comprehensive framework to deduce indicators for the health of ecosystems is still lacking (Cairns et al., 1993) or characterised by a poor theoretical underpinning (Mitchell et al., 1995).

This paper focuses on putting in order the huge quantity of environmental indicators, models, frameworks and building processes for indicators, leading to an outline of gaps with regard to our purpose - aiming at an ecosystem approach. Indicator requirements associated to environmental indicators are presented in detail. Additionally, we elucidate the process of indicator building, the various types of environmental indicators, their classification, and appropriate indicator models. Subsequently, we present how the diverse indicator types and models are embedded in indicator frameworks. We discuss the indicator types and models with respect to their capabilities, their transferability and applicability in the SPUEC context. In particular, the objectives of our paper are

- to compare the existing indicator types and models and their actual capabilities,
- to analyse what is usable for our intention, and
- to identify what is additionally needed for our purpose.

Based on this literature review we present a short overview of a new indicator model and derivation approach for ecosystemic effect indicators (EEI).

STATE OF THE ART OF ENVIROMENTAL INDICATORS

A historical overview about the development of environmental indicators was given by Rapport (1992). The author defines three main waves related to i) natural history ii) ecosystem sciences and iii) ecologically sustainable development. Our paper concentrates on recent developments in the fields of ecosystem sciences and sustainable development, whereas the environmental assessment approaches (SETAC, 1992; SETAC, 1993) etc. are not considered. Others are working on such impact assessment methods (e.g., de Haes et al., 1999; Hickie and Wade, 1998).

Definition

The items “environmental” and “ecological” indicator are often synonymously used in the indicator literature. However, according to Linster (OECD, 1998; pers. com.) environmental indicators include the ecological ones. The latter comprise the fields of ecology and ecosystem functioning in the narrower sense (Linster (OECD) 1998; pers. com.). In this article we examine environmental indicators.

Indicators are “simple things that are believed to reflect or “indicate” things that are not directly measurable” (Waltner-Toews, 1996). In general, an indicator represents a synthesis of information or data (OECD, 1993). In particular, however, almost every indicator article includes a different indicator definition. As Mitchell et al. (1995) stated, an indicator “transmits information concerning complex systems so as to make them more comprehensible”. Accordingly, McQueen and Noack (1988) termed an indicator “a measure that summarises information relevant to a particular phenomenon, or a reasonable proxy for such a measure”. An indicator is a variable, “hypothetically linked to the variable studied, which itself cannot be directly observed” (Chevalier et al. (1992) in Waltner-Toews (1994)). Thus a variable in “its generic sense is an operational representation of an attribute of a system and each variable has a set of possible values” (Klir, 1985). The latter was used by Gallopin (1994) as the basis to define indicators as “variables which may be nominal, ordinal or cardinal”, and “at given level of aggregation they are definable as individual variable, as functions of other variables or as correlated with other variables”. A similar point of view is taken by Bakkes et al. (1994) and van Harten et al. (1995) who point out that indicators are measurable variables or pieces. For instance, indicators describe the state of biotic and abiotic resources that should be reached and kept in the long run with regard to spatial and temporal concerns (Kalk et al., 1995). We define an indicator as a measurable variable which characterises systems or system components by reducing complexity and integrating information.

Use of indicators

The main task of environmental and ecological indicators is to steer actions (Bakkes et al., 1994), to provide easily accessible information, to improve communication about the state of the environment and to aid in environmental policy (Walz et al., 1997). Environmental indicators are used for the following purposes:

- **Demonstrating the progress towards goals and objectives** (Mitchell et al., 1995).
- **Synthesizing masses of data** (Mitchell et al., 1995).
- **Communicating data** to discipline experts, policy makers, non-experts or the public (Mitchell et al., 1995).
- **Environmental monitoring** for the characterisation and observation of the condition and quality of ecosystems (Hunsaker et al., 1993), their parts and the whole environment, particularly for an early warning (Arndt et al., 1996). Indicators assess the impact of stressors on one or several objectives (Bockstaller et al., 1997). Environmental monitoring is partitioned into i) monitoring the factors influencing the environment and the current situation, ii) the assessment and evaluation of the environmental condition and iii) the prognosis of the further development of the environment (Zierdt, 1997).
- **Formulation of environmental measures** as the basis of technological approaches for environmental quality (Rennings, 1994).
- **Environmental controlling** of enterprises, production systems or management activities for the identification of the appropriate target groups of environmental policy measures (Münchhausen and Nieberg, 1997).
- **Facilitating political decision making** and setting of priorities (Müller and Wiggering, 1999).

- **Evaluation of environmental measures** (e.g., for agricultural policy), assessing the success of environmental protection measures, testing political success and assessing policy consequences (Münchhausen and Nieberg, 1997).
- **Expression of interactions** of ecology and economy for an economic environmental evaluation (Zieschank and Nouhys, 1995).

Indicator requirements and selection criteria

The specific goal or purpose of each investigation planned determines the formulation of the indicator requirements. It is obvious that differences in requirements for environmental indicators exist. Consequently, an exact description of such requirements is essential. The indicator selection follows the criteria previously determined. Cairns et al. (1993) arrived at the following list of ideal indicators (table B1):

Table B1: List with ideal indicators differentiated into indicator requirements and criteria for indicators ordered into more scientifically and application relevant tasks (Cairns et al., 1993). Some of the characteristics summarise the background information necessary before an indicator is scientifically defensible. The requirements which are of special interest and great importance to our indicator development are bold

Scientific features	**Application features**
1. **Sensitive** to stressors without an all or none response	10. Socially relevant
2. Diagnostic of the stressor causing the problem	11. **Broadly applicable**
3. **Integrative**	12. Measurable
4. Biologically relevant	13. Interpretable
5. Non-destructive of the ecosystem	14. Cost-effective
6. Continuity in measurement over time	
7. Of an **appropriate scale**	
8. Non-redundant	
9. **Timely** (providing information quickly enough)	

Other authors present similar requirements (table B2). Moreover, Griffith (1998) provided an overview of recent articles and further references. The various indicator requirements and selection criteria can be assigned to a hierarchy: from general to specific. The specific criteria tend to relate to the technical application, whereas the general criteria are more related to the goals and objectives. Important to the applicability of indicators are the “three Rs”: robustness, relevance and reliability (Rapport, 1990).

Table B2: Indicator requirements and criteria for indicators as presented by various authors, combined and classified into two categories: scientific and application features. Only the more universal requirements are listed below. The requirements which are of special interest and great importance to our indicator development are bold. Compiled after Bockstaller and Girardin (1999); Braat (1991); Gallopin (1997); Girardin and Bockstaller (1997); Müller (1998); OECD (1993); Pankhurst et al. (1997); SRU (1994); SRU (1996); Turco et al. (1994); van Harten et al. (1995); Walz et al. (1997)

Scientific features	**Application features**
Sensitivity	**Data availability**
Predictive meaning	**Methodological transparency**
Problem relevance	Comprehensibility / easy interpretation
Scientific basis, methodological transparency	Broad applicability
Reflection of some aspect of **ecosystem functioning**	Measurability (readily available or available at reasonable costs)
Quantification	International comparability and compatibility
Possibility of aggregation	Feasibility
Representativeness	Justifiable effort
Relevance of endpoint	Cost effective
Reproducibility	Participation by the public in the use
Space scale relation	
Time scale relation	

The mutually exclusive nature of some of the characteristics (table B1; B2 and B11) is often disregarded. Usually, it is necessary to develop indicators scale-related. Species, population or sub-community level indicators are more sensitive than ecosystem-level properties (Schindler, 1990). Consequently, indicators at low biological and spatial scales (molecular, cellular level) often show low ecological relevance and predictive value. However, they are highly stress specific, indicate short-term responses and are characterised by a high signal-to-noise ratio. Indicators of higher spatial scales (communities, ecosystems) show high ecological relevance and predictive values. They have a low stress specificity and indicate long-term responses (Gentile and Slimak, 1992). It may be possible to predict ecosystem-scale effects of previously unstudied perturbations by knowing their most sensitive targets in the ecosystem. Sensitivity concerns the material and non-material inputs due to agricultural production as well as the possible effects and changes within ecosystems. The sensitivity of the indicator affects the integration of temporal variability (Breckling and Müller, 1997; Schubert, 1991). Single stresses may cause diverse effects depending on their timing and the susceptibility of the recipient ecosystem (Rapport, 1992). This necessitates a consideration of the spatio-temporal scale of the exposure as well as the time scales of response when selecting and evaluating ecosystems' response (Hunsaker et al., 1993). This means examining short-term and long-term sensitivities.

An accordant scale is important not only for the goal intended but also for the implementation process of the indicators. For instance, if an indicator reflects a national scale it is not suitable for a farmer. It must be noted that in some cases (e.g., in the phase of decision making) highly aggregated indices or macroindicators (appendix 1) are necessary. In other cases disaggregated single indicators are needed, e.g., during the problem identification phase.

Other requirements for indicators are ease of data collection and minimal costs. The indicator should be measurable using standard procedures with documented performance and a low measurement error.

To develop indicators for assessing environmental impacts of agriculture on ecosystems it is essential to get reliable and quantitative information about the manifold effects on environmental targets and ecological functions. The environmental indicators needed for that purpose have to meet a series of requirements. They must be highly sensitive. They should be relevant to the objective they indicate with a functional linking to the stressor. The deduction of the indicators should be scientifically based. Their integration capability should to be high. Integration capability in this context means that the indicators should be capable of integrating different receptors as well as interactions of different inputs whether they are synergistic (e.g., soil tillage and decomposition of pesticides (Düring and Hummel, 1992) or antagonistic. Furthermore, the indicators should be transformable into decision aid instruments. Moreover, the needed indicators should permit distinctions between production intensities and types of ecosystems concerning the hemerobie, e.g., all degrees between highly anthropogenic systems and natural systems (Kowarik, 1988) should be made.

Indicator building

The top-down and the bottom-up procedures

In principle, there are two main approaches to the evaluation of environmental degradation at the community and ecosystem level (Gentile and Slimak, 1992; Hunsaker and Carpenter, 1990; Munkittrick and McCarty, 1995). The top-down method directly assesses alterations in ecosystems. Subsequently, problems and causative agents are determined top-down (Cairns et al., 1993). By evaluating the multiple and cumulative effects of chemical and non-chemical stresses the approach is particularly appropriate for the regional and global scale (Gentile and Slimak, 1992). A similar procedure is used in deriving indicators. Starting with a defined goal, it is resolved into a number of objectives (figure B1) which are necessary to fulfil this goal (Hansen and Oestergard, 1996). Subsequently, the objectives are subdivided into causal factors and finally into indicators. Indicators then represent the degree to which the goal is achieved (Rennings, 1994). The top-down procedure only considers already discovered problems, and may not be suitable for new problems (Zieschank et al., 1993).

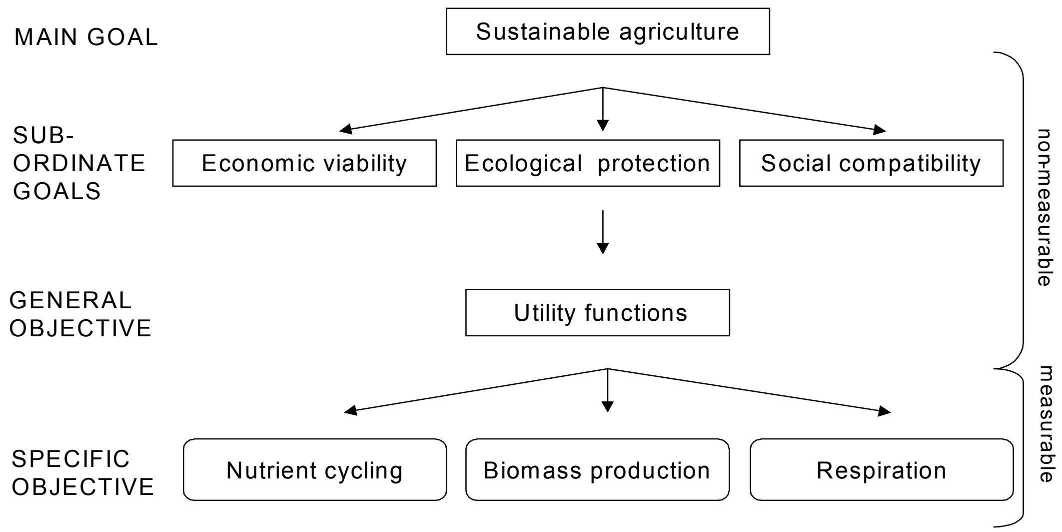

Figure B1: The procedure from the non-measurable superior goal (sustainable agriculture) top-down to the general objective (utility functions) and the directly measurable, specific objectives

On the other hand, bottom-up methods apply laboratory data of effects on simple systems to develop a paradigm reflecting more complex natural ecosystems. Indicators may also be developed bottom-up. Starting with a detailed and complete description of a current situation, e.g. degradation of different receptors by an impact, one aggregates the potential indicators and selects to the top, represented by macroindicators (SRU, 1994) (figure B2). Unlike the top-down approach, the bottom-up approach may be not goal adequate (Zieschank et al., 1993).

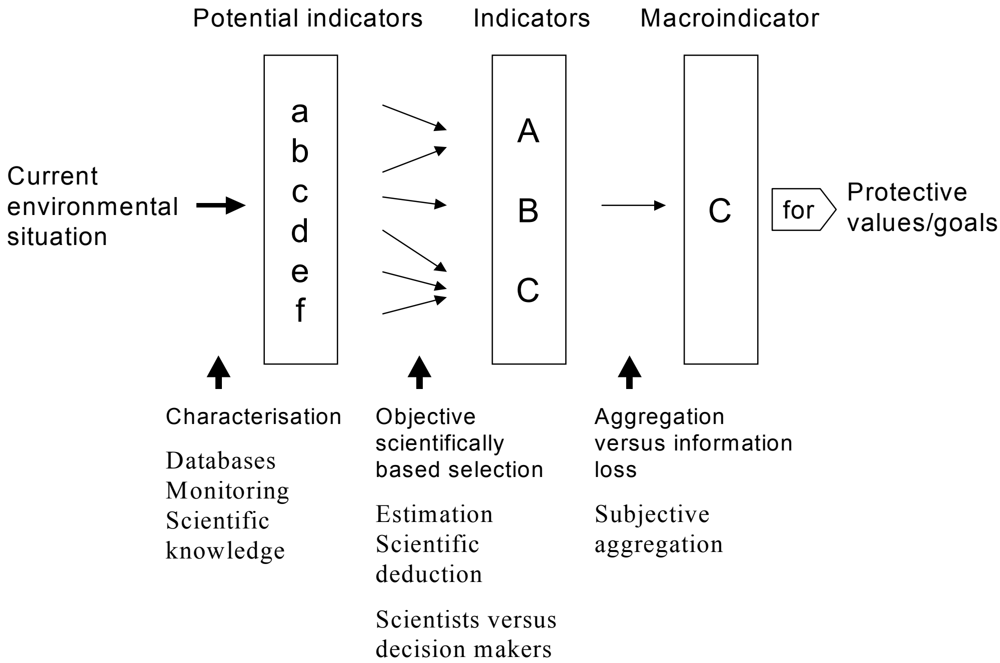

Figure B2: The bottom-up approach: the aggregation of potential indicators and specification of macroindicators

The most promising procedure to yield appropriate results is a combination of both bottom-up and top-down. It is necessary to aspire a synthesis: deriving indicators with the top-down approach and aggregating them in a bottom-up direction (Müller et al., 1998).

The process of indicator building and selection

The words indicator building, construction, creation, derivation, development, as well as elaboration are synonymously used in literature. Even "selection" is applied with the same meaning. But to provide basics for policy and decision makers requires a consistent use of terms that reflect the same ideas.

To build indicators broad management and policy goals, protective values and explicit ecosystem objectives must first be formulated. The indicators suitable for the problem which has to be solved must be determined (Beese, 1996). Indicators are always developed according to an objective. Usually, concepts deduce single indicators or indicator sets to “translate” the defined values and goals into measurable parameters.

Many of the currently available environmental indicators have been selected from preexisting lists with little or no modification (Mitchell et al., 1995). The process of indicator building is often non-transparent in available indicator models. Frequently, indicators are presented without specifying the selection process. Often they are developed with very subjective expert questionnaires (Münchhausen and Nieberg, 1997; Nieberg and Isermeyer, 1994), or one falls back upon existing ones. Notwithstanding we have identified seven steps for the indicator building (figure B3).

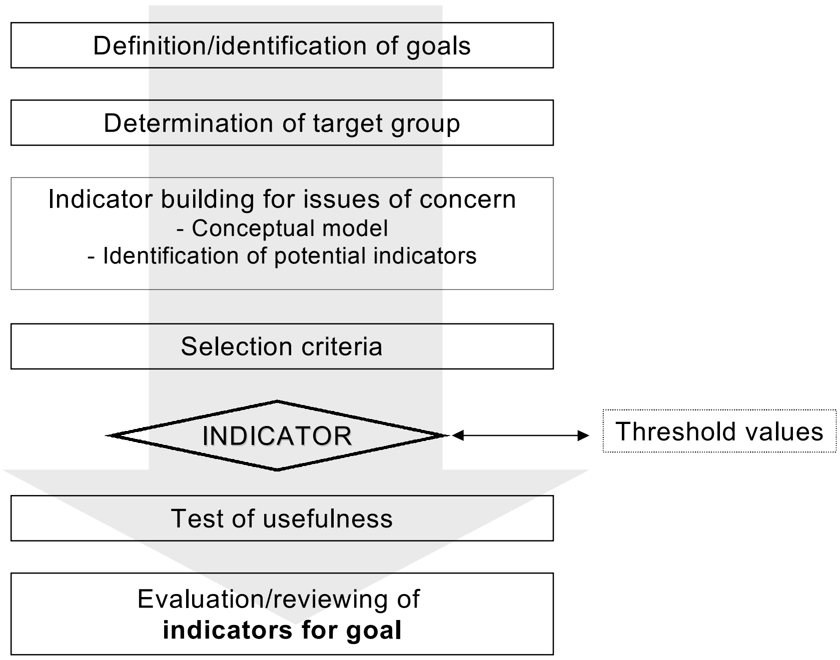

Figure B3: The building and specification of indicators, seven steps for the indicator elaboration/building

1. **Definition/identification of goals** (SRU, 1994). Indicators cannot be identified until goals and objectives are specified and values and targets are determined (Doppler and Vandré, 1999). The main, non-measurable goal can be broken into general objectives (Cairns et al., 1993) which are replaced by measurable ecosystem objectives (figure B1). The objectives represent the basis for the indicator derivation (SRU, 1998).

2. **Determination of the target group**. The end-user for whom the indicators are tailored must be defined (scientific community, planning community, policy/decision-makers, public etc). The degree of complexity of the information may be higher if the indicator is intended for an use by specialists (Braat, 1991).
3. **Indicator building for issues of concern**. Two main streams are pursued. Firstly, an estimation by authors is done. The indicators are formulated by the authors themselves or result from subjective expert questionnaires. This approach rapidly provides sets of static, case- and site-specific indicators. However, their use is restricted due to the lack of information about the development of the indicators and their low transferability. Secondly, a scientific derivation is performed. For some issues indicators should be newly constructed. This construction should be done scientifically and in consultation with those having relevant subject-knowledge (Mitchell et al., 1995). It results from a scientific examination of general functions, processes and structures of systems founded on a model-based perception of ecosystems (Young, 1997). This scientifically based deduction method requires extensive knowledge about the system under investigation. Such a deduction allows for systemic indicators and stands out by a high transparency as well as a good transferability.

   Different approaches to indicators are commonly used. Either a mass of data is taken and communicated using a series of highly specific indicators or the data is taken and a few composite indicators are constructed from them or a key indicator is taken as being representative of the full array of indicators (Mitchell et al., 1995; von Wirén-Lehr, 1999). The data is obtained from direct or indirect measurements as well as from modelling estimates. Qualitative data will be inserted in cases lacking in quantitative data. The indicator building includes the following: i) creation of a conceptual model; ii) identification of parameters (biotic and abiotic, Elliott, 1997) and listing of potential or candidate indicators; iii) checking for the data availability.
4. **Specification of criteria** for the assessment of the indicators (Walz et al., 1997). Comparison of the list of developed potential indicators with selection criteria (Walz et al., 1997), followed by the selection of the final indicators.
5. **Determination of references and threshold values**. To assess the progress towards an intended objective or the desirable state the indicators should be quantifiable. In cases where indicator values are already available the indicators may be compared to reference conditions. These are either sustainability criteria, policy targets or historical conditions. If indicator values are not available, it might be possible to deduce threshold

values from the constructed indicators. The reference system being a non-manipulated system offers the best guarantee for the preservation of the fundamental values. The closer one comes to the reference the larger the maintenance of ecological sustainability will be (ten Brink, 1991).

6. **Test of usefulness** (Bockstaller and Girardin, 1999). A validation test may assess whether the primary objectives have been achieved. Thus the theoretically developed indicators and their applicability are tested in a case study.
7. **Evaluation by experts**. Once the indicators have been developed, they should be reviewed by the target group for whom they are intended with regard to the previously defined requirements (Mitchell et al., 1995). For instance, the scientific community will evaluate indicators with respect to the indicator properties desired or the objectives of the indicator concept.

Classification of indicators

We fully agree with Rapport (1994) who stated "the indicators are not just one grouping, but a number of groups". Generally, manifold types of indicators can be distinguished according to their focus of characterisation, views (integrative/systemic or traditionally reductionistic), their functions, as well as their goals and objectives (table B3a, B3b). Since the beginning of the 1970s a partitioning of overall environmental indicators in ecosystem sciences into different types has been carried out. The main types treated were: response and stress indicators (Rapport, 1992). Stress has been defined as a detrimental or disorganising influence (Odum, 1985). At that time three foci evolved: "purity": mostly with regard to chemical purity but also to the concept of "pristine nature"; "ecosystem integrity" a concept that was not operationalised then, but having already tried to find key indicators. Better results, however, were obtained for disintegrities; and "amenities": i.e. nature's services (Rapport, 1992). Meanwhile, more indicator types appeared.

Environmental indicators may be divided into two categories:

- simple, case or site-specific indicators with a reductionistic view (table B3a)
- systemic functional indicators (table B3b).

Table B3a: Classification of available environmental indicators with an emphasis on simple indicators. The classification represents the authors' opinion of best fit. It is possible that some articles are more appropriate to other areas

Author	Indicator types	Derivation	Orientation	Target group	Spatial scale of use	Goal
		1: Estimation by authors or expert questionnaires 2: Scientific deduction 3: Not specified	1: Application 2: Theory	1: Scientific community 2: Planning, management community 3: Farmer 4: Policy/decision makers	1: Local scale 2: Regional scale 3: National scale 4: Global scale	1: Soil health/quality 2: Ecosystem health/integrity 3: a) Sustainability/ sustainable development b) Sustainable agriculture 4: Environmental monitoring/reporting
(Arndt et al., 1996)	Bioindicators * (accumulation indicators, reaction indicators)	1	1	1	1, 2, (3)	4, (2)
(Bockstaller and Girardin, 1999; Bockstaller et al., 1997; Girardin and Bockstaller, 1997)	Simple indicators Composite indicators	2	1	3	1, 2	3b
(Braat, 1991)	Predictive indicators Retrospective indicators	1	1	1, 2, 4	3	3a

Author	Indicator types	Derivation	Orientation	Target group	Spatial scale of use	Goal
(Cairns et al., 1993)	Compliance indicators Diagnostic indicators Early warning indicators	1	1, 2	2, 4	1, 2	2, 3a, 4
(Costanza, 1994)	Vigor indicators Productivity indicators Resilience indicators	3	2	1		2
(Dick, 1997)	Bioindicators	3	1	1	1	1, 4
(Doran and Parkin, 1994; Doran et al., 1996; Doran and Safely, 1997)	Soil quality/health indicators	1	1	1, 2	1, 2	1, 3a
(Doube and Schmidt, 1997)	Bioindicators	1, (2)	1	1, (3)	1, 2	1
(Dubsky et al., 1998)	Agri-ecological indicators	1	1	1, 4	2	3b
(Elliott, 1997)	Bioindicators	3, (1)	1, 2	1	1	1, 3a
(Friend and Rapport, 1991; Rapport and Friend, 1979)	Stressor indicators Response indicators	2	1	4	3	4
(Gilbert, 1996)	Sustainability indicators	1, 2	1	1, 2	1 - 3	3a
(Gunkel, 1994)	Bioindicators	1	1	1	1	4, (2)
(Halberg, 1998)	Resource use indicators environmental impact indicators	1	1	3, (4)	1, (2)	2
(Hansen and Oestergard, 1996; Hansen, 1996)	(Sustainability) indicators	1, (2)	1	1, 3, 4	1	3b

Author	Indicator types	Derivation	Orientation	Target group	Spatial scale of use	Goal
(Harris et al., 1996)	Soil health indicators Soil quality indicators	1	1, 2	1, 2	1	1, 3b
(Hoffmann-Kroll et al., 1995)	State indicators Impairment indicators	1	2, (1)	1, 4	3, (2)	4
(Hülsbergen and Diepenbrock, 1997)	Agro-environmental indicators	2	2	1, (3)	1	3b
(Hunsaker and Carpenter, 1990)	Stressor indicators Exposure indicators Habitat indicators Response indicators	3	1	1, 2	2, 3	4
(Karlen and Stott, 1994; Karlen et al., 1997)	Soil quality indicators	1	2, (1)	1	2, (1), (3)	1, 3a,b
(Lorenz et al., 1997)	Pressure indicators State indicators Impact indicators Response indicators	3	1	2	2, 3, (1)	3a
(Luxem and Bryld, 1997)	Indicators of sustainable development	3	1	4	3, (4)	3a
(Mathes et al., 1991)	Ecological indicators	3	2	1	1	4
(McCullum et al., 1995)	Soil quality indicators Soil health indicators	3	2, (1)	1, 2	1	2
(Mitchell et al., 1995)	Sustainability indicators	2, (1)	2	1	1 - 4	3a
(Münchhausen and Nieberg, 1997)	Agro-environmental indicators	1	1	1, 4	2, 3	4

Author	Indicator types	Derivation	Orientation	Target group	Spatial scale of use	Goal
(Nieberg and Isermeyer, 1994)	Agro-environmental indicators (direct indicators, indirect indicators)	1	1	3, 4	2	3b
(OECD, 1993; OECD, 1997)	Pressure/driving force indicators State/condition indicators Response indicators	1	1, (2)	1, 4	3, 4	3a, 3b, 4
(Opschoor and Reijnders, 1991)	Pressure indicators Environmental effect indicators	1	2	1	2, 3	3a
(Radermacher et al., 1998)	Descriptive indicators Normative indicators Stress indicator Impact indicators (accumulation, effect, risk)	3	2	1, 4	3	3a, 4
(Rapport, 1992; Rapport, 1994)	Ecological indicators (diagnostic indicators Risk indicators Synoptic or bottom-line indicators “healthiness” indicators)	3	1, 2	1, 4	2, 3	2, 3a
(Roper and Ophel-Keller, 1997)	Bioindicators	3	1	1	1	1

Author	Indicator types	Derivation	Orientation	Target group	Spatial scale of use	Goal
(SRU, 1994)	Source indicators Dispersion and transformation indicators Impact indicators	3	1	1, 4	3	3a, 4
(Syers et al., 1995)	Sustainable land management indicators	3	1	1	1, 2, 3	3
(Turco et al., 1994)	Microbial indicators	1	1	1	1	1, 3a
(Walz et al., 1997)	Pressure indicators State indicators Response indicators	1	1	1, 2, 4	3	4
(Zierdt, 1997)	Nature indicators	3	1	1, 2	2	4
(Zieschank et al., 1993)	Scarcity indicators Denaturing indicators Stress indicators Impact indicators	1	2, (1)	1, 4	3	4

( ): limited useable for that issue

*Bioindication as part of ecotoxicoloy differentiates three essential groups (Arndt et al., 1996): active, passive biomonitoring and bioindication with synecological aspect (indicating concrete key reactions in ecosystems depending on dominant organisms)

Table B3b: Classification of available environmental indicators with an emphasis on systemic indicators. The classification represents the authors' opinion of best fit. It is possible that some articles are more appropriate to other areas

Author	**Indicator types**	**Derivation** 1: Estimation by authors or expert questionnaires 2: Scientific deduction 3: Not specified	**Orientation** 1: Application 2: Theory	**Target group** 1: Scientific community 2: Planning, management community 3: Farmer 4: Policy/decision makers	**Spatial scale of use** 1: Local scale 2: Regional scale 3: National scale 4: Global scale	**Goal** 1: Soil health/quality 2: Ecosystem health/integrity 3: a) Sustainability/ sustainable development b) Sustainable agriculture 4: Environmental monitoring/reporting
(Beese, 1996)	Analytical indicators Joint indicators Systemic indicators Normative indicators	3	2	1	1, 2	(2)
(Dilly and Blume, 1998)	Orientors	3	2	1	1, 2	3a
(Gallopin, 1997)	Sustainability indicators	3	1	4	3	3a
(Gupta and Yeates, 1997)	Bioindicators	1	1	1	1	1

Author	Indicator types	Derivation	Orientation	Target group	Spatial scale of use	Goal
(Müller, 1998; Müller and Wiggering, 1999)	Functionality indicators	2	1, 2	1, 4	1, 2, 3	2
(Sparling, 1997)	Bioindicators	1	1, (2)	1	1	1
(ten Brink, 1991)	Amoeba as an indicator	2	1	1, 4	1, 2, 3	3a
(van Straalen, 1997)	Community bioindicators	2	1, (2)i	1, 4	1	1, 4
(Xu et al., 1999)	Structural indicators Functional indicators Ecosystem level indicators	3, (1)	2	1	1	2
(Young, 1997)	Sustainability index	3	2	1	3	3a

( ): limited useable for that issue

In tables B3a, and B3b we propose a classification of indicator approaches according to our categories simple and systemic. We give an overview about the various ideas shared in the indicator literature.

The systemic indicators will be considered in more detail, since we aim at an integrative systemic approach. Beese (1996) created indicators based on ecosystem functions, especially the multifunctional use of forests. He developed indicators located on different hierarchical levels which permit the examination of the actual state of the ecosystem and its development. Finally, an evaluation is included. The functionality indicators deduced by Müller (1998) are based on the background of ecosystem theory. The goal represents ecosystem integrity. Integrity means that the main orientation of ecosystem protection is to maintain the organisation of the ecosystem and the development in self-organising process sequences (Kay, 1993). The functionality indicators are based on system orientors partly being essential processes and functions of ecosystems. These indicators serve to answer concrete questions, e.g., for the framework of the German Environmental Economic Evaluation. However, they allow neither an assessment of impacts nor the determination of limits for impacts and inputs.

Existing indicator models and approaches

Frequently, the various indicator types form part of an indicator model. By means of indicator models it is tried to describe relations between economy and ecology (Hoffmann-Kroll et al., 1995). These models consist of a frame of different horizontal categories juxtaposed with accordant indicators (e.g., state or response indicators, figure B4). The ecologically oriented models are based on simplified schemes of linkages between ecological and economic systems (Rennings, 1994). In general, assumptions regarding cause/source-effect-chains are explicitly named. Often, these causal models assume linear relations between the human activities and the environment, being aware, however, that the real relations are more complex (OECD, 1993), e.g., due to spatial and temporal scale transitions.

Dominant are stress models like the Canadian Stress Approach (Friend and Rapport, 1991; Rapport and Friend, 1979). The Pressure-State-Response approach (OECD, 1993) which was derived from the Canadian Stress Approach applied to ecosystems (Rapport and Friend, 1979) is rapidly gaining international prominence. Originally ‘response’ stood for ecosystem response (Bakkes et al., 1994). Nowadays, it is mainly used to denote the response of society (Gallopin, 1997; OECD, 1993). An overview of the most relevant available indicator models and approaches is given in table B4.

Table B4: Characteristics of existing indicator models that are mostly cause-effect oriented, their purpose, indicators and limitations concerning our intention

Model	**Stress**	**Pressure-state-response**	**Actor-acceptor**	**Source-transmission-effect**
Purpose	Rely ecosystem and man in a system connection	Integration of environmental decision making	Economic evaluation of the environment	Determination of environmental quality standards
Indicator types	Stress/stressors Response	Pressure Condition Response	Cause/actor Acceptor	Emission Transmission Effect
Assumption	Existence of spatially related environmental report system	Determination of state through impact of society	No linear cause-effect-chains; cognitive conducted relation	Estimation of the whole damage potential
Limitations	Simplified cause-effect-chains No consideration of ecological functions Regional or higher scale	Minor consideration of effects International or national scale Main focus on state conditions	Mainly economic evaluation Functions and structures not considered National scale	Indicator categories not sufficiently filled with usable indicators
Reference	(Friend and Rapport, 1991; Rapport and Friend, 1979)	(OECD, 1993)	(Zieschank et al., 1993)	(SRU, 1994)

Stress Response Environmental Statistic System Approach (STRESS) (Friend and Rapport, 1991; Rapport and Friend, 1979)

The aim of the Canadian model is to relate environmental stress, its impact on and reactions of ecosystems and/or man in a system. Its focus lies on the interface between the production-consumption activity of man and the transformation of the state of the environment. Stressors are outputs like emissions, which have a certain extension in space and which could alter the natural and human environment. Stress is the pressure exerted by stressors (e.g., the spatially determined inputs like concentrations and depositions) on the environment. Two types of indicators are divided: the first type are stress indicators and stressors (human activities as sources of stress on ecosystems) partitioned into six main sources of stress. The second type are responses (Friend and Rapport, 1991; Rennings, 1994). Environmental response to stressor activities are distinguished from human collective and individual responses to environmental degradation and resource depletion (Friend and Rapport, 1991; Rapport and Friend, 1979). The model aims at the regional or higher scale and does not consider ecological functions. A critical point of this model is the simplified cause/source-effect-chains (Rennings, 1994). They do not reflect the much more complex reality of ecological effect interrelations. Therefore, the Stress approach might be better regarded as a kind of a classifying system.

AMOEBA-Approach (ten Brink, 1991)

AMOEBA is a general method of ecosystem description and assessment. The setting of a verifiable ecological objective is a prerequisite for the approach. A reference system, a historic or current reference area relatively undisturbed, is always needed in this approach. Having used indicators of the actual environmental situation ten Brink (1991) developed an ecological index (non-weighted addition of the indicator deviation from a reference circle) related to state conditions. The AMOEBA approach was applied to the North Sea and major rivers in the Water Management Plan. Further, the approach can be applied to many other systems at diverse scales. The AMOEBA approach appears to be of reasonably universal applicability (Bakkes et al., 1994). However, it is also oriented towards real objects and limited to the monitoring of the actual state, and does not allow ascertaining limits of impacts on ecosystems considered.

Pressure-State-Response-Approach (PSR) (OECD, 1993)

This model aims at the integration of ecological aspects during economic decision making and at the employment of indicators in environmental performance reviews. The model is based on the assumption that actions of the economic system (production, use of resources) always influence the state of the environment by loadings. In turn, environmental alteration necessitates reactions of the economic system. Thus the model belongs to the cause-effect related type. However, the Driving Force-State-Response model states that there is yet no causality implied among indicators between cells, neither horizontally (driving force-state-response) nor vertically (social-economic-environmental-institutional) (Gallopin, 1997; OECD, 1997). Three types of indicators are subdivided in this model: pressure, state and response indicators with regard to environmental performance. Recently, the term pressure was modified into driving force (D) (OECD, 1997; UN, 1995). The DSR-Model addresses the issue of sustainable development with a consideration of the ecological and the human subsystem. The limiting issues of these two models, PSR and DSR, with respect to the needs of the SPUEC project are models' orientation on the national or international scale, a primary focus on state conditions and a minor integration of environmental effects.

Actor-Acceptor-Model (AAM) (Zieschank et al., 1993)

The model was developed for an economic assessment and evaluation of the environment starting with its actual state. Economic activities may ensue negative accompaniments which should be considered in societal decision making. Therefore, this model is intended to gather environmental alterations. The model belongs to the cause-effect related type. There are six types of indicators in this model dedicated to sources of environmental loading, environmental media (air, water) and impacts. Transport and effects of inputs through environmental media are also implied. Acceptors are real objects in the environment which are touched by impacts. The indicators do not describe linear cause-effect-chains. Rather, they indicate “a heuristic meaning, a cognitively conducted relation” (Zieschank et al., 1993). The methodological basis of this approach is the ecological risk analysis. Initially the method uses a top-down approach, later, to differentiate full-scale and textual issues, a bottom-up approach is used. The approach examines at the national scale. Ecosystem functions or structures are not regarded in this approach.

Source-Transmission / Transformation-Effect-Model (STE) (SRU, 1994)

The STE-Model aims at determining environmental quality standards. It is based upon effects on different targets and considers cause-effect-chains. All acidifying substances have to be summed up in a whole acid damage potential. For example, it is not sufficient to regard only one acidic substance, e.g., H_2SO_4. Three types of indicators are used: i) emissions and structural interventions/changes, ii) transmission, transformation and accumulation and iii) effects on targets. These types of indicators are not sufficiently defined and not yet applicable.

Further approaches to indicators belong to the fields of **life cycle assessment**, **risk and environmental impact assessment**, which are not examined in this review. Examples of this type of research represent the approaches of Belaoussouff and Kevan (1998); Cairns (1998); de Haes et al. (1999); Gentile and Slimak (1992); Giampetro (1997); Hickie and Wade (1998); Hunsaker et al. (1993); ISO (1998); Lenz, (1999); Klein and Klein (1990); SETAC (1993); van der Werf (1996).

Indicator frameworks

The terms “indicator systems” and “indicator framework” are interchangeably used. Indicator frameworks or systems are the superstructures incorporating societal values and goals. They include indicator models with manifold indicator types, an assessment and evaluation. For example, the Actor-Acceptor-Model was developed for the framework of the German Economic Ecological Evaluation (Zieschank et al., 1993).

There is no framework that generates indicators for every purpose (OECD, 1993). Several analytical frameworks have been utilised comprising a “sector approach” - checking indicators of environmental impact from the point of view of economic sectors. There is also the “media approach” which considers living resources, air, water and land. Further on, the “goals approach” selects indicators in accordance with administrative mandates (Gallopin, 1997). The purpose of an indicator framework should be to organise the process of indicator selection and development (Cairns et al., 1993) as well as to organise individual indicators or indicator sets in a coherent manner. To establish an indicator system requires decisions concerning indicator types, classification of environmental problems, spatial and sectoral aggregation (Walz et al., 1997). The frameworks can help to identify data collection needs. The guidance of overall data and of information collecting processes are additional uses (Gallopin, 1997).

Options and limitations of environmental indicators and indicator models with regard to sustainable production

Huge sets and types of indicators are accessible today. Moreover, many indicator models are available. Nevertheless, the review revealed that current indicator concepts are characterised by the following drawbacks:

Firstly, there is a lack of transparent and comprehensible derivation procedures that can be applied case- and site-unspecific in the field of sustainable agriculture. As pointed out, strategies to deduce indicators which are scientifically based are accessible (Cairns et al., 1993; Mitchell et al., 1995; Xu et al., 1999). However, the derivation of indicators for sustainable agriculture is often unclear, since existing approaches with other goals (e.g., ecosystem health or sustainable development) have not yet been transferred to agricultural production. Indicator sets have to be suitable to describe the condition of various systems with reference to systemic and dynamic aspects of sustainability. Considering the agricultural production system as one compartment of the whole landscape cultured, indicator sets providing information not only on imbalances (e.g., releases) of the agricultural production system itself are required. Indicators should also characterise external depositions and off-site effects of emissions resulting from agricultural production (e.g., toxic effects in aquatic ecosystems due to pesticide residues). Such indicators should be independent of specific system conditions. A model-based deduction of indicators is able to meet these requirements, e.g., based on an analysis of system key functions or elements (Mitchell et al., 1995). The new type of indicators introduced for our project to assess impacts of agricultural production on ecosystems requires a transparent derivation method.

Secondly, systemic integrative indicators indicating the impact of loadings from agriculture on the one hand and being meaningful for ecosystem functioning on the other hand are lacking. We demonstrated that there are many case- or site-specific indicators (table B3a).

Available indicators are specific to the process which they are part of and are always designed with an explicit target group in mind (Braat, 1991). There are no universal sets of environmental indicators (Bakkes et al., 1994). However, it is essential to create indicators that can be assigned to different systems and altering conditions considering long-term as well as short-term effects. Reactions, i.e. effects upon, for example, ecological processes, and related indicators with respect to time and space scales in adjacent ecosystems can vary to a great extent (Kümmerer and Held, 1997; Ulrich, 1993). Outputs from a source may travel short distances to a sink over short times or they need long time to travel long distances. Understanding of ecological functioning developed on small scales cannot be easily extended to larger scales. The diverse sets of mutually reinforcing ecological processes leave their imprints on spatial and temporal patterns at different scales (Peterson et al., 1998).

One recommendation for the improvement of existing indicators is the development of modelling the linkages between source and effect to the greatest extent possible (Müller and Wiggering, 1999). The question is, how these causes and effects on various scales may be linked? A model similar to the PSR model is assumed to be a useful taxonomy for ordering indicators but without an underlying functional causality (Gallopin, 1997). Still remaining is the indication of the functional linkage between the outputs of production processes and the effects in sinks, e.g., upon ecosystems with respect to time and space scales.

The systemic-integrative nature of many aspects of sustainability reinforces the importance of searching for whole system variables for which appropriate indicators can be derived (Gallopin, 1997). Notwithstanding the above mentioned indicators are frequently reductionistic, regarding only one aspect of a system without considering the whole system. Looking at the currently available indicator types one recognises that there are many sectoral indicators, especially in the field of bioecology. Integrative ecological approaches for the protection of the environment against loadings of dangerous substances are, to a great extent, lacking. Already existing are indicators that aggregate or integrate information of loadings. However, these indicators were created for other scales, e.g., national or international levels and are difficult to transfer to local or regional scales.

The main emphasis of source or pressure indicators lies on the description of emissions or on the continuos registration of impacts. Hence source indicators can be one part of the indicator model required to characterise the emissions of production systems. State and impact indicators are restricted to the recording of the actual environmental situation and the consequences of impacts. At most, a comparison with the desirable environmental situation is possible. Besides the rather sectorally oriented indicators, others exist aiming at systemic-integrative, functional views (Beese, 1996; Müller, 1998). In the foreground, these indicators regard the state of the environment. They can be assigned to the type state indicator. These indicators give an overview of the actual situation and the temporal development of the environment (Hoffmann-Kroll et al., 1995). The state indicators are mainly useful for monitoring and controlling. The response or reaction indicators are anthropozentric. They represent the response of society to recorded environmental problems, e.g., management indicators for farmers to develop ecologically harmless practices. This indicator type may be applied in our intention.

We have to note that often no clear distinctions are made between impact and management indicators relating to human reactions (Wahmhoff 1998, pers. com.). We should clearly separate these two types of indicators. An effect-related indication ensures broad scientific discussions. Having a full description from source (e.g., the agricultural production) to sinks (e.g., a lake) allows for a clear elucidation of options concerning emission reduction.

In recent research, no empirically gathered indicators for the functionality of ecosystems can be found (Hoffmann-Kroll et al., 1995; Müller and Wiggering, 1999). Attempts for the derivation of such macroindicators can be seen in Müller et al. (1998). Schneider and Kay (1994a,b) identified thermodynamic non-equilibrium, exergy flows and exergy gradients as holistic indicators recommendable for ecosystem functions. Yet, these indicators are not directly applicable, do not indicate the effects of inputs on ecosystem functions and do not allow a quantitative determination of limits.

As a consequence integrative, systemic indicators for the goal of sustainable agriculture must be developed based on the specific objective of the utility functions (figure B3). The needed indicators must be ecologically oriented and scientifically based.

Thirdly, the available indicator models and the associated frameworks are not directly applicable to our purpose and were often constructed with another scale in mind. Often, they aim at the national or international scale whereas we aim at the local (ecosystem) or regional (landscape) scale. It is possible to assume the coarse frame of existent indicator models for our purpose. A combination of the PSR- and the AAM-model with three indicator types is conceivable. However, the indicator types need further development. They must be differently defined. Since they are intended to support farmer decisions, it is necessary to create indicators that can be transformed into decision aid instruments directly related to producer and user practices.

In summary, promising indicator concepts have been proposed. However, the available models are not directly applicable to assess agriculture, in particular to achieve "ecological sustainability" that is oriented on ecosystem functioning. Thus a modification, combination or a further development of existing indicator concepts is needed to achieve the targets of SPUEC. We prefer a primarily causality chain oriented model consisting of three types of indicators. The source-(state)effect-reaction (SER) systematic (figure B4) is related to the main constituents of the Pressure-State-Response model, representing best the intention of the SPUEC project. The first indicator type, the stress indicators, examine the source of pressures and causes from the agricultural production system for alterations of the ecosystems, e.g., emissions. (1, figure B4). Next, in general, the state indicators indicate the quality, state or condition of the environment that may arise from various driving forces (OECD, 1997). But we need indicators showing effects on the affected ecosystems (2, figure B4). Thirdly, the reaction indicators express the responses of the environment, policy or society, to the actual and perceived alterations in the environment. The development, selection and use of the environmental indicators which are utilised to characterise the response of ecosystems to various impacts will be crucial to attain the purpose intended (Ward, 1992). The need of information about reactions and decisions of the producers and users in the form of management indicators has emerged for our project (3, figure B4).

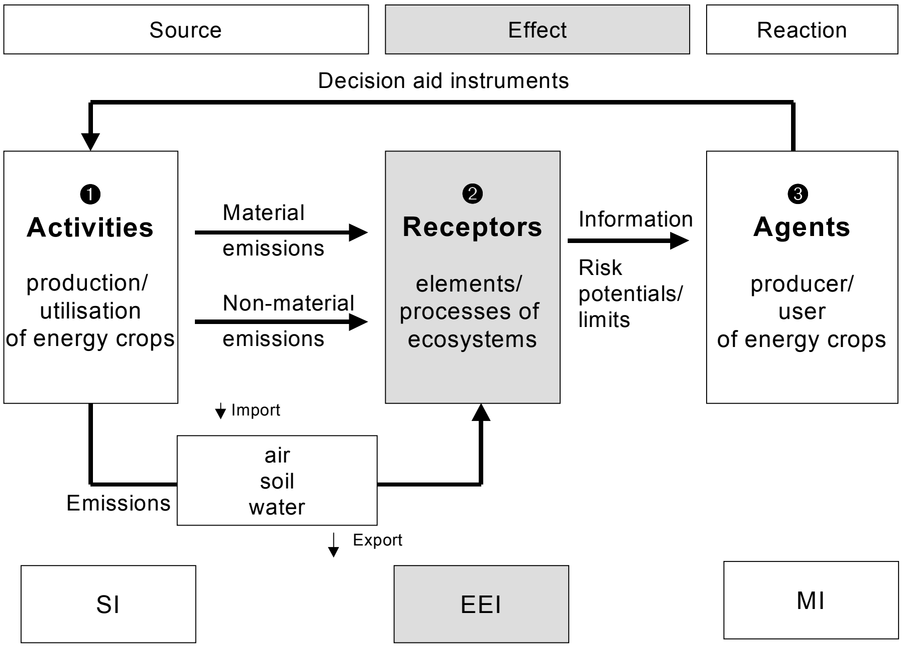

Figure B4: Frame of the projects' stressor-effect-reaction model (SER) aiming to bring SPUEC in relation to affected ecosystems. SI: stress indicator, EEI: ecosystemic effect indicator, MI: management indicator. Area marked in grey is the ecosystems part for which EEI are to be developed. Source means the activities (1) resulting of the SPUEC such as fertiliser and pesticide use, soil tillage, transport of energy crops, burning of the crops, etc. The resulting outputs, their transport in air, soil or water and their transformation have to be summed up in stressor indicators. Receptors (2) for all material and physical inputs in the affected ecosystems exist. The EEI are derived to assess the effects of SPUEC. Determining acceptable ranges or limits with these effect indicators, allows the dissemination of information and decision aid instruments to the agents (3).

Methodologically on the ecosystems' part three steps are considered necessary. To start with, the affected ecosystems are identified and described. Furthermore, protective values and target objectives must be set (Doppler and Böcker, 1999). These can be the utility functions (de Groot, 1992; Fränzle et al., 1993). Secondly, from these functions ecosystemic effect indicators (EEI) are derived (Merkle and Kaupenjohann, 2000a). Thirdly, the indicators are used to ascertain thresholds or acceptable ranges.

METHODOLOGICAL APPROACH TO DERIVE ECOSYSTEMIC EFFECT INDICATORS

The SPUEC project intends to derive indicators for the whole ecosystem functioning. This will facilitate cause-effect-assessments of inputs. The principle of combining both top-down and bottom-up approaches for the indicator development is applied to build the EEI. The approach integrates ecosystem functioning (e.g., the objective utility functions) and inputs resulting of the agricultural production process. Our indicator derivation procedure includes three steps: 1. Compilation of a list with characteristics of each ecosystem function considered (top-down). 2. Compilation of a list with potential effect indicators for a certain input (bottom-up). 3. Overlapping of the two lists and identification of the specific EEI. The procedure can be seen in detail in Merkle and Kaupenjohann (2000a). Subsequently, a test of the indicators in a case study follows (Merkle and Kaupenjohann, 2000b).

CONCLUSIONS AND FUTURE TASKS

The analysis of existing environmental indicator literature revealed that there are manifold indicator types and indicator models. Various concepts address different issues of concern, e.g., sustainability/sustainable development, ecosystem health/integrity and environmental monitoring. Concepts and approaches of environmental impact and risk assessment were not regarded in this review.

Indicators are usually developed by i) estimation by authors or ii) a deduction scientifically based. However, we pointed out that transparent methods of indicator derivation are rare. Nevertheless, seven steps that are necessary for the indicator construction have been identified: the definition of goal determines the subsequent methodological steps. The next steps are: the determination of the target group (scientists, farmers, landscape planners or policy makers); the indicator building according to the issues of concern (conceptual model, data gathering, listing of potential indicators); a specification of selection criteria; the determination of references and threshold values; a test of usefulness (case study). The last step is the evaluation of the developed indicators by experts.

Most environmental indicators may be assigned to the categories i) simple and ii) systemic indicators. Despite the variety of available indicators we could not identify indicators suitable for analysing ecosystems affected by outputs of agricultural production processes.

The reviewed indicator models are mostly oriented on a causality chain regarding different indicator types. Often, the indicator models were created for an extensive description of relations between economy and ecology and aim at the national or global scale. They contain diverse indicator types. Source or pressure indicators indicate emissions or the continuos registration of impacts. State or condition indicators examine the registration of the actual environmental situation and the consequences of impacts. Response or reaction indicators show the responses of society to recorded environmental problems.

We conclude that we must develop a comprehensible and transparent indicator derivation approach for our project with a new type of systemic, function-oriented indicators: the ecosystemic effect indicators. The indicators are embedded in an indicator model on the ecosystem scale (local and regional).

Next, our indicator derivation approach (Merkle and Kaupenjohann, 2000a) will be tested experimentally. A case study will be carried out for this purpose. A further step is to develop and present sets of effect indicators for the various ecosystems affected. This has been done for an agroecosystem (Merkle and Kaupenjohann, 2000b). Additionally, we will derive EEI for a close to nature ecosystem.

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APPENDIX

Indicator: Measurable variable which characterises systems or system components by reducing complexity and integrating information

Ecosystemic effect indicator: Receptors which are sensitive to material and non-material inputs. EEI indicate the functioning of ecosystems

Macroindicator: Aggregated, whole system describing indicators

Indicator model: Frame of different juxtaposed horizontal types of indicators. The types are related to each other, each type indicating and describing another part of the considered problem issue and making sense in combination with the others

Indicator framework: Superstructure incorporating societal values and goals, an indicator model with different indicator types, and an assessment or evaluation

C DERIVATION OF ECOSYSTEMIC EFFECT INDICATORS - METHOD

ABSTRACT

Anthropogenic activities and agricultural production in particular release material emissions and energy into the environment. Hence, production causes side effects in ecosystems. To assess these effects integrative system-level indicators are needed. Numerous environmental indicators are available, however, lacking is a sound theoretical basis. Accordingly, the derivation of indicators is often unclear and non-transparent. Frequently, environmental indicators aim at monitoring and controlling, only integrating sectoral aspects. The associated indicator models were often created for the assessment of relations between anthropogenic actions and the environment on a national or global scale. Systemic, functional, holistic indicators are rare. Due to the gaps of indicator research a new category of indicators and an approach for their derivation is necessary. In this paper we present the idea of ecosystemic effect indicators (EEI) and propose a conceptual approach to deduce these indicators. Thus a set of indicators can be derived that is tailored to the needs of the indicator user, but remains rooted in the principle of ecosystem functioning. The indicators demonstrate the relationship between agricultural production and its effects in the agronomic production system itself and adjacent ecosystems. Depending upon both ecosystem functioning and inputs, ecosystemic effect indicators must fulfil certain requirements. They provide information to assess loading capacities of ecosystems. By transferring the indicators into decision criteria they are applicable for the farmer. Recently, the applicability of the proposed conceptual approach is tested in a case study.

INTRODUCTION

Agricultural production releases material and non-material emissions into the environment. After being transported and transformed the resulting depositions and concentrations affect the environment on different scales. The effects in ecosystems are to be analysed. In the discussion about impacts of agriculture on ecosystems it is important to get reliable and quantitative information about the various effects on environmental targets and functions. Much knowledge about effects and impacts of agricultural production is available. However, in most cases the research was limited to individual components, concentrating on single compartments or specific environmental media (Müller, 1992).

Approaches devised for individual components dominate both the production systems side and the ecosystems side. To account for the holistic character of systems the present paper attempts to realise an integrative approach. We treat the outputs from the production system into the environment on the one hand and the inputs into adjacent ecosystems on the other hand. System outputs include material and non-material emissions, matter and energy (refer to Odum, 1991), emitted from the production system, e.g., nutrients, soil pressure, NO_x etc. Harvest goods are not included. System inputs into ecosystems are energy or matter emitted by the source system, e.g., nutrients, pesticides and heavy metals which may affect an ecosystem. In case of the agronomic production system the system outputs concurrently represent inputs in the agroecosystem as affected ecosystem itself.

This study is part of an interdisciplinary project on sustainable agriculture titled “Sustainable Production and Utilisation of Energy Crops“ (SPUEC) in which the utilisation of energy crops forms part of the production system. The supply of energy from organic substances is assumed to be ecologically sustainable if none of the affected agroecosystems including their functioning is irreversibly changed by outputs from the energy supply system in the long run (Härdtlein et al., 1998). The project takes a system approach. Thus the required indicators should be rooted in ecosystem functioning specified by the utility functions. Our understanding of “ecological sustainability” implicates that the possibility of further development of the ecosystems and their parts needs to be ensured. Ecosystems are affected if their functioning is impaired by emissions of the production and utilisation of goods. As affected ecosystems are considered both the agronomic production system itself as well as other adjacent systems (e.g., aquatic, oligotrophe or forest ecosystems).

Often a reductionistic approach dominates the understanding of the components of the production system as well as these of the ecosystem. The complexity of systems is only seen in parts and the interrelationships are not well understood (Haworth et al., 1996). It is necessary to develop an instrument to represent the complex relationships between effects of external inputs and ecosystems. So far, there are many concepts, case studies and models to evaluate agronomic production systems economically. That is not sufficient from the ecological point of view, however. Recently, there has been considerable discussion about sustainability which incorporates economic, social and ecological aspects. The latter needs loading capacities or target values which preserve systems functionality. An integrative ecological assessment including both emissions from production systems and environmental effects in ecosystems has to be set first in the discussion of sustainable production.

Indicators represent a valuable tool when direct measurements cannot be realised (Bockstaller et al., 1997). An indicator is a variable "hypothetically linked to the variable studied, which itself cannot be directly observed" (Chevalier et al., 1992 in Waltner-Toews, 1994). Here we define an *indicator* as *a measurable variable which characterises systems or system components by reducing complexity and integrating information*. Thus indicators can serve as instruments to show complex relationships and to simplify them. They might be used to express the difference between the actual environmental state and the desired one (SRU, 1994). The main task of environmental indicators is to steer actions (Bakkes et al., 1994) and to provide easily accessible information. Environmental indicators also serve for an improvement of the communication about the state of the environment and they aid in environmental policy (Walz and al., 1997). Often such indicators aim at environmental monitoring or the control of enterprises, production systems or management activities for the identification of the suitable target groups for environmental policy measures (Münchhausen and Nieberg, 1997). Indicators are mostly specific to the process they were developed for.

Although there are huge sets of indicators available (Merkle and Kaupenjohann, 1998, subm.) integrative system-level indicators for the functionality of ecosystems that are empirically gathered are still lacking (Hoffmann-Kroll et al., 1995; Müller and Wiggering, 1999). Most indicators are reductionistic and consider only a few components of the system. The indicators available are often based on real objects or actions/activities (Bockstaller et al., 1997; Nieberg and Isermeyer, 1994), but not on ecosystem functions. However, environmental sustainability requires the maintenance of environmental functions and potentials in the long run (Beck, 1998). Thereof ensues a need for indicators depicting functions and showing the effect of inputs on these functions.

Indicator models, e.g., the pressure-state-response-model (OECD, 1993) or the actor-acceptor-model (Zieschank et al., 1993) were mainly created for a national or global scale. They are needed to evaluate the discrepancies between the state of the environment and the desired environmental quality. These models aim at assessing the interrelationships between economic and ecological systems.

Frequently, the available indicators are not based on a sound concept. Comprehensible methods for their derivation are lacking (Cairns et al., 1993, Lorenz et al., 1998). Therefore, the new category of indicators introduced for our purpose also requires a transparent derivation approach. In this paper we present a conceptual approach for our purpose aiming at the assessment of complex relations between SPUEC and the environment using EEI.

ECOSYSTEMIC EFFECT INDICATORS (EEI)

The systemic-integrative nature of sustainability points out the importance of system-level parameters for which appropriate indicators have to be devised (Gallopin, 1997). We aim at deriving indicators for the ecosystem functioning and facilitating cause-effect-assessments of inputs due to production processes, e.g., SPUEC. Based on a literature review (Merkle & Kaupenjohann, 1998, subm.), we propose a new category of indicators: EEI which are defined as follows:

>> *Ecosystemic effect indicators are receptors sensitive to material and non-material inputs. They indicate the functioning of whole ecosystems.* <<

Receptors are spatial or functional parts of the environment which can be located on diverse hierarchical levels, e.g., the groundwater, the pore volume, plants or microorganisms, and which respond to inputs. An earthworm may be such a receptor, e.g., for fungicides. It is an important element for the matter decomposition, nutrient supply, hence for the whole nutrient cycle.

The effect indicators have to bridge the gap between societal goals, targets and environmental quality standards. In comparison to existing approaches, we refer to the target “preservation of ecosystem functioning“. In contrast to other approaches the effect indicators should not serve for a continuous environmental observation and monitoring. They should indicate, when - at which concentration -, and how - according to the impairment of a function - an input affects a receptor. As a result the assessment of loading capacities is enabled. Consequently, the status of the effect indicators have only to be defined once.

Requirements

EEI shall fulfil certain requirements for the SPUEC. Firstly, such indicators have to be meaningful for the ecosystem functioning. Secondly, they must be highly sensitive regarding the material and non-material inputs due to agricultural production as well as regarding the potential effects and changes. Sensitivity needs to account for both temporal variability within a year and its integration (Müller et al., 1998; Schubert, 1991). Single stresses can have manifold effects depending on their timing and the susceptibility of the recipient ecosystem (Rapport, 1992). Therefore, it is necessary to consider time scales of response in selecting and evaluating ecosystems response (Hunsaker et al., 1993) with regard to both short-term and long-term sensitivities. Thirdly, the effect indicators should be capable to integrate interactions of diverse inputs (a synergism, e.g., soil tillage and decomposition of pesticides or an antagonism). Fourthly, it is intended to provide decision support for the farmers. There is a necessity to identify indicators from which decision criteria can be deduced for agricultural management practices. Thus, the indicators desirably must be functionally linked to the sources of inputs and their effects. Determining risk potentials or loading capacities with these effect indicators, provides information and decision criteria to the farmers to maintain and achieve, rspectively, the “ecological sustainability“.

Moreover the data availability has to be taken into consideration for the application of effect indicators. Knowing which indicator is needed for the indication of inputs from SPUEC in affected ecosystems, the next step is to outline how to derive the EEI by relating inputs and the ecosystem functioning.

DERIVATION OF ECOSYSTEMIC EFFECT INDICATORS

Supposition

We propose a conceptual model to identify effect indicators. The model is based on a hierarchical concept of ecosystems. At least, four hierarchical levels may be distinguished in ecosystems (O'Neill et al., 1986; Beese, 1996). The specific levels of organisation are linked to specific spatial and temporal scales (Wagenet, 1998). The highest level (III) in ecosystems is the overall ecosystem functioning including the utility functions like regulation, production, habitat and career (Fränzle et al., 1993; Gilbert and Janssen, 1998). Level II consists of superior relations (interactions) between subsystems (Doppler, 1998), level I are subsystems i.e. elements plus processes between them, and level 0 consists of elements (biotic, e.g., species or abiotic, e.g., soil structure). While the ecological functions aim at ecosystem health, the production function has also to incorporate a socioeconomic component because system assessment without that component is incomplete (McCullum et al., 1995). Although the major focus of our approach is ecological sustainability, the maintenance of environmental quality needs also to incorporate economic and social issues. This aspect is implemented by considering the production function.

Procedure

In principle, either a top-down or a bottom-up approach for the indicator derivation exist (Gentile and Slimak, 1992; Munkittrick and McCarty, 1995). The societal goals and valued targets are firstly identified and defined in the top-down approach. Secondly, the requirements are set depending on the goals. Thirdly, available indicator sets and models are analysed and assessed (SRU, 1994). Starting at a very high level of aggregation of the data pyramid aggregation levels decrease step by step dependent upon the purpose. The indicators resulting reflect the degree of achieving of the (societal) goals, e.g., ecosystem health or sustainable agriculture. A limitation of the top-down approach is that not for all issues adequate indicators already exist (Rennings, 1994). An example for the top-down approach is the work about functionality indicators of Müller (1998). In his work the basic goal represents ecosystem integrity.

The bottom-up approach starts with a detailed description of the current situation of the issue under consideration, but without a concrete goal definition. By identifying the most appropriate receptors for inputs and afterwards selecting and/or aggregating them, the developed indicators are integrated into existing concepts or indicator models. The bottom-up approach may not be adequate in achieving of specific goals (Zieschank et al., 1993) as goals are not explicitly defined beforehand.

We combine both the top-down and the bottom-up approach for the derivation of EEI. The top-down part of our indicator derivation starts at the ecosystem functioning (figure C1) which is rendered precise through the utility functions, a clearly set goal definition. Descending from the highest level, i.e. the ecosystem functioning, the resolution gets finer and finer. Ecosystem functioning is described by many characteristics which can be elements, processes, properties or part functions. The characteristics of the levels II to 0 should be identified. As many receptors as possible are identified for the input part bottom-up. Afterwards the necessary receptors are related to the ecosystem function under consideration and then selected. By combining the top-down and the bottom-up part a link between functioning and inputs ensues. The corresponding indicators represent processes, part functions etc., and are also diagnostic for an effect of the stress exerted on the ecosystem. The general procedure may be explained by the following example:

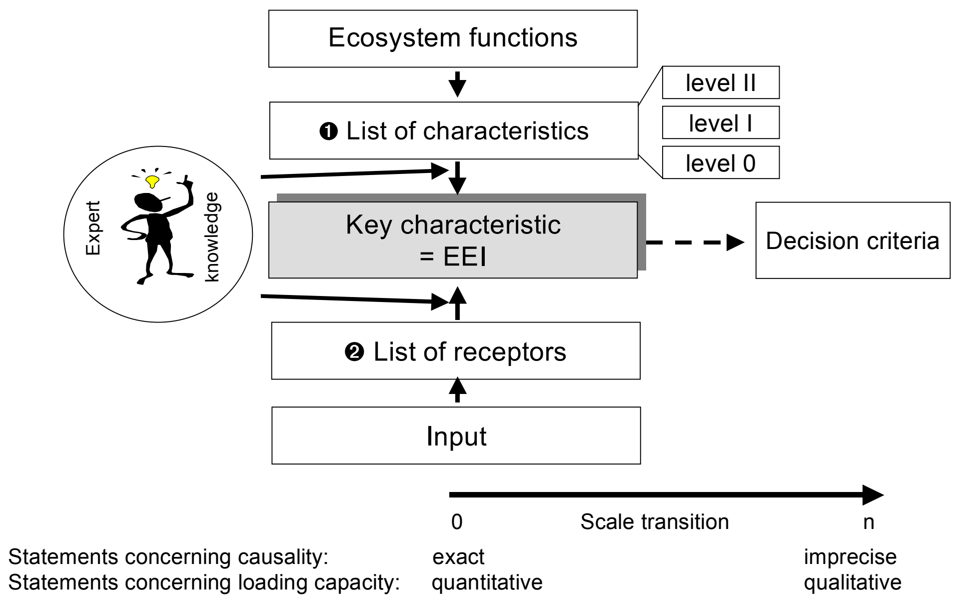

Figure C1: Procedure for the derivation of ecosystemic effect indicators

To start the procedure, firstly choose an affected ecosystem (e.g., the agroecosystem). Secondly, choose a specific ecosystem function, e.g., the production function. Find out all important characteristics at the different levels (0, I, II) for the chosen function ❶ (figure C1). Thereby keep in mind potential effects of the considered input. A broad range of characteristics ❶ results, e.g., nutrient cycling, soil aeration, aggregation etc. The list of characteristics is oriented on functions. These characteristics may be called potential indicators. Thirdly, regard one input, e.g., soil pressure, and its potential effect on the selected function. For the chosen input identify and compile elements, processes etc. influenced by the specific input. A second result will be a list of receptors ❷, potential effect indicators, which is oriented on inputs (stress). In case of soil pressure the soil structure, infiltration capacity, porosity etc. are influenced. These receptors can be chosen based on the effect on particular characteristics at certain concentrations or magnitudes of stress.

An approach to simplify this procedure may be to establish two classes in order to reduce the huge size of potential indicators. The spatial extension of processes and structures is low while process frequencies are fast at lower hierarchical levels. Higher levels have greater spatial extension but lower frequencies of process signals than lower ones. Moreover higher levels constrain lower levels due to their larger time constraint (Wagenet, 1998). Stress also determines space and time frequencies. Therefore one class (i) has to contain the elements or processes of the diverse organisation levels differentiated into the specific space and time scale they operate on. The other class (ii) has to include the tact and frequencies of the specific input. The key characteristic we look for has to be situated at a comparable organisation level. Starting point for this approach might be the soil subsystem which plays a key role for the whole ecosystem covering buffer capacities as well as the storage for matter and energy.

The final step of the procedure, the identification of the EEI is the decisive one. Find out the intersection between ❶ and ❷ based on expert knowledge. The two lists of characteristics and the potential indicators, are compared and overlaps are created. This intersection, key characteristics of the specific ecosystem, will contain EEI. Such indicators depend upon the specific function and the input under consideration. The porosity has been established as ecosystemic effect indicator for the production function and the input soil pressure in the example.

The algorithm has to be applied for each ecosystem function and each input of interest. Finally, sets of effect indicators for the selected ecosystem will be resulting. Later on, sets of EEI for all ecosystems considered will be available.

A further goal is to develop decision criteria. After the definition of thresholds the decision criteria can be derived of the EEI. In the example above porosity can be transferred into loading frequencies or the weight of tillage machines allowed.

POTENTIALS AND LIMITATIONS OF EEI

With the conceptual model for the derivation of EEI we developed an approach as much as possible reproducible. McCullum et al. (1995) already stated that some form of standard to assess measurements of system components would be ideal.

The approach implies the development of specific indicators for various production systems and production intensities because the bottom-up part of our approach starts at the specific input (kind and quantity). We solve the problem cited in literature (Gallopin, 1994) that to differentiate indicators referring to land use, management practices and production intensities is difficult by including the diverse inputs respective their intensities already at the beginning.

Increasing complexity across level 0 to III in ecosystem hierarchy leads to a general problem during indicator derivation: Indicators should be most integrative on the one hand. This requirement would prefer indicators on high levels. On the other hand increasing complexity evokes the problems to trace cause-effect-relationships. The EEI derived by our approach indicate typical characteristics of the ecosystem functioning (derived top-down) which are at the same time affected by an input (derived bottom-up). We develop indicators which portray the link between ecosystem functioning and inputs through this approach.

Ideally indicators should have target values that characterise desirable conditions (McCullum et al. 1995). If it is not possible to determine limits, a desirable trend direction should be stated at least (Mitchell et al., 1995). EEI should as much as possible allow to ascertain scientifically based, quantitative limits or target values in form of critical loads or critical physical impacts, e.g., a level of soil pressure that must not be exceeded to ensure soil structure stability in order to avoid erosion. Another example might be a load of Cd that must not be exceeded to avoid leaching into the groundwater. Concerning an evaluation, the threshold values for key indicators are only applicable with the knowledge that they will vary depending upon land use, site specific properties, ecosystem or landscape. In many cases these specific values (thresholds, standards etc.) embody a subjective value judgement (Gallopin, 1994). Moreover the assessment of a specific function of greatest concern as part of the ecosystem functioning has to be performed first (Doran et al., 1996) which also implies subjectivity.

The determination of quantitative loading capacities for the EEI is independent upon the distance between production site and affected ecosystem. However, in cases where the affected ecosystem is far away from the production site (cf. n on the transition scale, fig. C 1) this quantification shows no direct link to the outputs from the production system. Thus cause-effect-relationships between outputs from the production site and the inputs and effects resulting in ecosystems cannot be quantitatively traced. Direct and quantitative linkage will usually become impossible as scale transitions in the transport chain will introduce a variety of additional or concurrent impacts complicating the cause-effect-relationship. Hence if production site and affected ecosystems have to be linked across scales the decision criteria for agricultural production derived of the effect indicators (refer to figure C1) become qualitative. The more scale transitions have to be considered the more qualitative becomes the decision criteria, e.g., a range of pesticide amount which must not be exceeded or riparian vegetation that has to be established.

CONCLUSIONS AND FUTURE TASKS

A variety of indicators and indicator models is available. However, neither a method to bring the effects of agricultural production, in particular of SPUEC, in relation to the affected ecosystems and their loading capacities exists. Nor there is an useable integrative, system-level indicator type. Thus with this paper we propose an approach for the derivation of effect indicators for ecosystems.

The EEI provide information about the cause-effect-relationship between production processes and their effects on the affected ecosystems. Therefore, they serve as useful tools in the assessment of SPUEC. To maintain “ecological sustainability“, knowledge concerning the loading capacities of effects on ecosystem functioning is needed. Such loading capacities or target values could be critical levels, critical physical impacts, critical loads or risk potentials. We conclude that these loading capacities may be quantitatively ascertained on the basis of the EEI derived in our approach. This might only be possible in a qualitative manner for adjacent ecosystems.

Thus in the next step we will develop EEI for an agroecosystem. A further step is to develop and present sets of effect indicators for the various types of affected ecosystems, e.g., for “in a natural state” ecosystem. The applicability of the indicators will then be tested in a case study in south-western Germany. Furthermore their conceptual and operational validity must be proved.

Finally, the ecosystemic effect indicators have to be implemented in an indicator model regarding also indicators for the driving forces and reactions of the SPUEC.

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D ECOSYSTEMIC EFFECT INDICATORS FOR AGROECOSYSTEMS

ABSTRACT

Side effects of agricultural productions in ecosystems have to be assessed. To support the sustainability of the ecosystems system-level indicators are needed. Various environmental and sustainability indicators are accessible, but the theoretical underpinning is often poor or even missing. Therefore, we have derived a method to deduce ecosystemic effect indicators which are adapted to the needs of the indicator user. Depending on incoming inputs and utility functions of ecosystems, ecosystemic effect indicators are developed by combining a top-down and a bottom-up approach. Such ecosystemic effect indicators are mainly enrooted in soil characteristics or processes that form an essential basis for the whole ecosystem functioning. In this paper we implement our previously presented indicator derivation procedure. Our approach is tested in a case study. The ecosystem functioning is level-dependent characterised. As an example of an impact the soil pressure is categorised in view of its effects in agroecosystems. Finally, a set of indicators for agroecosystems which relates emissions of agricultural production to the affected agroecosystem itself is presented. The macro porosity ensues as ecosystemic effect indicators for the habitat function, the respiratory intensity and the metabolic quotient for the transformation function, the pore spectrum for the filter function, the penetration resistance or the macro porosity for the production function and the field capacity for the storage function. Relating these indicators to threshold values as far as they are available in literature allows quantitative statements within the frame of sustainable agriculture.

INTRODUCTION

Agricultural production frequently causes undesirable effects in ecosystems. To judge environmental impacts of agriculture especially with respect to sustainability it is essential to get quantitative information about the manifold effects on environmental targets and ecological functions.

We demonstrate an instrument and its application to assess the effects of emissions and releases of agricultural production with regard to ecosystems. Special focus will be laid on the agroecosystem itself. The aim is to link emissions and releases (= outputs, e.g., leaching of pesticide residues or phosphorus from fertiliser application) from agriculture with ecosystems (e.g., lakes or forests). This enables to relate the depending effects on functions and elements to threshold values in ecosystems.

Currently, knowledge about effects and impacts of agricultural production processes on ecosystems is accessible. However, research has been focussing on single compartments or individual systems in most cases. Moreover, many instruments remain restricted to the characterisation of the agricultural production system itself. There have been little efforts to link production systems with ecosystems in order to assess their mutual impairment on a system level.

Recently, there has been increasing concern of sustainability that encompasses economic and social as well as ecological aspects. The latter which is object of investigation within our project need loading capacities or target values that preserve ecosystem functioning.

Affiliated is the present study to an interdisciplinary project on sustainable agriculture. To discuss sustainable agriculture an integrative ecological assessment including both outputs from production systems and environmental effects in ecosystems has to be set first. This objective will be achieved by means of indicators. Previously, we have developed an approach to deduce ecosystemic effect indicators (Merkle and Kaupenjohann, 2000a).

This paper focuses on the implementation of our indicator derivation procedure proposed in a former study. In summary (1) the goal ecosystem functioning with respect to the target 'utility functions' is characterised. (2) Effects of agricultural production in ecosystems are illustrated by means of a case study. Exemplary soil pressure is analysed for the manifold inputs. (3) Finally, we propose and discuss a set of ecosystemic effect indicators (EEI) for an agroecosystem.

Ecosystem functioning

Protection always requires the setting of values and target objectives (Doppler and Böcker, 1999). Up to now, there is no consensus on general targets of nature conservation

(Doppler and Vandré, 1999). In order to achieve quantifiable targets of ecological sustainability we address ecosystem functioning as a prerequisite of system sustainability. If the system is sustainable it is also healthy (Rapport, 1994).

Lavelle (1996), Fränzle (1998) and Herrick (2000) bring the soil into the focus of all terrestrial ecosystems because it is one of the principal regulating compartments. It plays a key role in sustainable land use (Harris et al., 1996). The soil condition is vital to both food and fibre production and ecosystem functioning (Doran and Safely, 1997). Soil represents the starting point of our consideration for the chosen target, the utility functions (de Groot, 1992; Fränzle et al., 1993), which are important for the whole ecosystem. The following functions are subsumed under the item "utility":

- Regulator function, subdivided into i) filter: capability of mechanical retention regarding particles and colloides; ii) buffer: retention capacity for dissolved substances by chemical processes, e.g., sorption; iii) transformation: potential of biotic transformation of natural and xenobiotic substances.
- Habitat function: quality for being used as substrate for animals, biota and plants.
- Storage function: ability to store water, nutrients and the genetic pool.
- Production function: capacity of food and plant production.

First three compiled represent ecological functions aiming at ecosystem health, whereas the production function incorporates also a socioeconomic component.

Since ecosystems are hierarchically organised complex systems (Müller, 1992; O'Neill et al., 1986), diverse levels can be distinguished where higher system levels control lower ones. In turn, the potential of higher ones is restricted by the behaviour of the lower (O'Neill et al., 1986). Ecosystem functioning subdivided into the utility functions is located on the highest level. Thereunder succeeds the level (II) of superior relations between subsystems (e.g., food-chains or cycling), followed by the level (I) of subsystems (e.g., decomposition encompassing elements, like earthworms, and single processes, like shreddering) (Brussaard et al., 1997). The lowest level of our view (0) is the level of elements (e.g., bacteria or soil aggregates).

Agricultural outputs and their effects

The undesirable outputs of agricultural systems may be differentiated into material emissions (e.g., pesticide or fertiliser residues) and non-material releases (e.g., soil pressure). These emissions and releases can be regarded as inputs into adjacent ecosystems after transport and transformation. In case of considering the agronomic production system itself as affected ecosystem, outputs and inputs are identical.

Effect may be defined as an enrichment of pollutants above the normal concentration or as a physical impact (Arndt, 1987). In Gregor et al. (1996) and Umweltbundesamt (1993) effect directly refers to the impact of pollutants. Being chronic or acute effects must be distinguishable from any natural variation. The gravity of an effect depends on the temporal sensitivity of a receptor (Fränzle, 1998; Wiens, 1989), e.g., in spring while growth the soil macrofauna is much more sensitive for inputs than in autumn. Each output affects different spatial and temporal scales. Outputs cause various effects which directly or indirectly impact organisms, resources or processes. The toxic contamination by pesticides, soil erosion after tillage, element leaching after fertiliser application, acidification of adjacent lakes or nutrification of neighboured fens may be exemplary mentioned (Haber and Salzwedel, 1992; Stahr and Stasch, 1996; White, 1997). Effects are more or less complex and evolve from effect chains or effect networks (Doran et al., 1996; Müller and Wiggering, 1999), e.g., acidification provoking mobilisation of heavy metals or a decrease in biodiversity. Effects can also pass across hierarchical levels (Reagan and Foldham, 1992).

Several unfavourable consequences of agriculture have been extensively studied, e.g., nutrification, acidification, pollution or erosion, whereas soil deterioration was less investigated. However, it should be stronger considered because subsoil compaction by vehicles with high axle loads seems to pose the most severe long-term threat to soil productivity (Hakansson, 1994).

We focus on soil pressure as an input on the agronomic production site. The pressure and duration of the mechanical loading are the decisive parameters. The resulting compaction in soil is load and time dependent. Wheel and axle loads on the one hand and speed and frequency of passes on the other hand are significant parameters responsible for changes of soil structure (Dürr et al., 1995). For Russian condition Rusanov (1991) found that increasing tractor weight leads to yield losses of up to 35%. The accelerated mechanisation in agriculture and the enhancement of machinery weights are main factors causing soil compaction (Lipiec and Simota, 1994). Thus the consequences for future soil productivity are object of increased concern, predominately the risk of permanent deterioration of subsoil (Hakansson, 1994).

Compaction has been estimated to be responsible for the degradation of an area of 33 million ha in Europe (van Ouwerkerk and Soane, 1994). That implies also economic issues. Compaction may contribute to increases in soil erosion and the loss of nutrients to atmosphere and groundwater. In turn, these effects affect social issues and economic losses on the farm-level.

The conflict to raise the productivity on the one hand and to ensure both the sustainable productivity as well as other soil functions on the other hand is crucial in pertaining soil compaction (Petelkau, 1998). This highlights the tensions between ecology and economy.

Two main temporal aspects have to be regarded: short-term effects, mainly consisting in plough layer or topsoil compaction and long-term effects, encompassing subsoil compaction (Hakansson and Medvedev, 1995). In the past, the ability of processes like wetting/drying, freezing/thawing or biological activity to reverse compaction were overestimated (Hakansson and Petelkau, 1994). Nowadays, subsoil compaction is assumed to be persistent (Hakansson and Reeder, 1994). Other long-term effects commonly are succession effects: water infiltration capacity decreases, water and wind erosion increase (Horton et al., 1994). Chemical processes are also influenced, e.g., a rise in anaerobic conditions with the consequence of nitrogen losses through denitrification. Accordingly, biological activity decreases. Thus, matter transformation is retarded. Compaction may even reduce biodiversity (Brussaard and van Faassen, 1994).

Effect indicators

The assessment of environmental effects by indicators is restricted due to the complexity of ecosystems. A quantification of cause-effect-relationships is hardly possible with respect to complex effect networks. Nevertheless, indicators are useful tools to reduce the complexity of system description and to integrate manifold system information (Bockstaller et al., 1997; Giampetro, 1997). Numerous single ecological and sustainability indicators as well as indicator frameworks are available (Bakkes et al., 1994; Freyenberger et al., 1997; Merkle and Kaupenjohann, 1998, subm.). However, deficiencies exist in comprehensible methods for indicator deduction, or, the frameworks were made using another scale (OECD, 1993; OECD, 1997). Established impact indicators address solely the impact of a single stress (e.g., tobacco - O_3) but do not depict ecosystem functioning. Joergensen (1998) advocates for ecological indicators that enable a reasonable assessment of ecosystem health and describe the damage caused by a pollutant at the ecosystem level. Obviously, a lack emerges concerning indicators which link agricultural action and ecosystem response.

Thus we have developed EEI which are defined as follows: "Ecosystemic effect indicators are receptors sensitive to material and non-material inputs. They indicate the functioning of ecosystems" (Merkle and Kaupenjohann, 2000a). The receptors are spatial or functional parts of the environment that can be located at different hierarchical levels and which respond to inputs (Merkle and Kaupenjohann, 2000a). Examples represent microorganisms, plants, the pore volume or the groundwater. This definition refers to living organisms or materials which are affected and includes interrelated collections of living organisms, i.e. ecosystems (Umweltbundesamt, 1993).

METHOD TO DEDUCE ECOSYSTEMIC EFFECT INDICATORS

Our study is exclusively based on available literature data. Similar to SETAC (1993) we have chosen a proceeding equivalent to life cycle impact assessment (LCIA) starting with an inventory analysis. Secondly, according to the classification step of LCIA data from the inventory analysis are grouped into effect categories. Three areas of protection are dishinguished as classes of endpoints in LCIA: human health, natural resources and natural environment (ISO, 1998). The main focus of our project lays on the latter two.

In this context we are not so much interested in the inventory and classification steps, but we also strive for effect characteristics. The third step in LCIA, the characterisation, is based on scientific knowledge about environmental processes. The outcome of the characterisation step may be referred to as effect profile consisting of a number of input measures or descriptions.

The main difference between the LCIA proceeding and the approach presented here is that our indicator derivation does not start at effect categories (e.g., global warming) but at defined targets (e.g., utility functions). Such targets can be adjoined to different effect categories.

Classification of emissions and releases and the depending inputs

The aim of this step is to outline which scales are affected as well as to assess the importance of an emission or a release. We study three main parts: Firstly, the preprocessing chains, production and utilisation encompassing the spatial and temporal kind of a source (e.g., point, area, periodic or continuos) and properties of the emission or release (e.g., persistence). Secondly, the transport and transformation (that link emission and release with input) which imply the discharge pathway and the kind of transport process are considered. Thirdly, effects of inputs in ecosystems including effect radius (local, regional, global), effect period (short-term or long-term) and effect place (e.g., lake) are addressed.

Ecosystemic effect indicator derivation

Often indicator deduction is performed without theoretical underpinning (Mitchell et al., 1995). Suitable indicators are selected by two main procedures: an estimation by authors or by expert questionnaires and a scientific derivation. The EEI approach is mostly assigned to the latter. Combining top-down and bottom-up approaches the proceeding relates an emission (e.g., soil pressure of tillage) and an ecosystem potentially affected (e.g., the agroecosystem). First step of the derivation procedure is to resume the characteristics describing the target and the corresponding partial targets top-down (figure D1). The characteristics are located on diverse hierarchical levels.

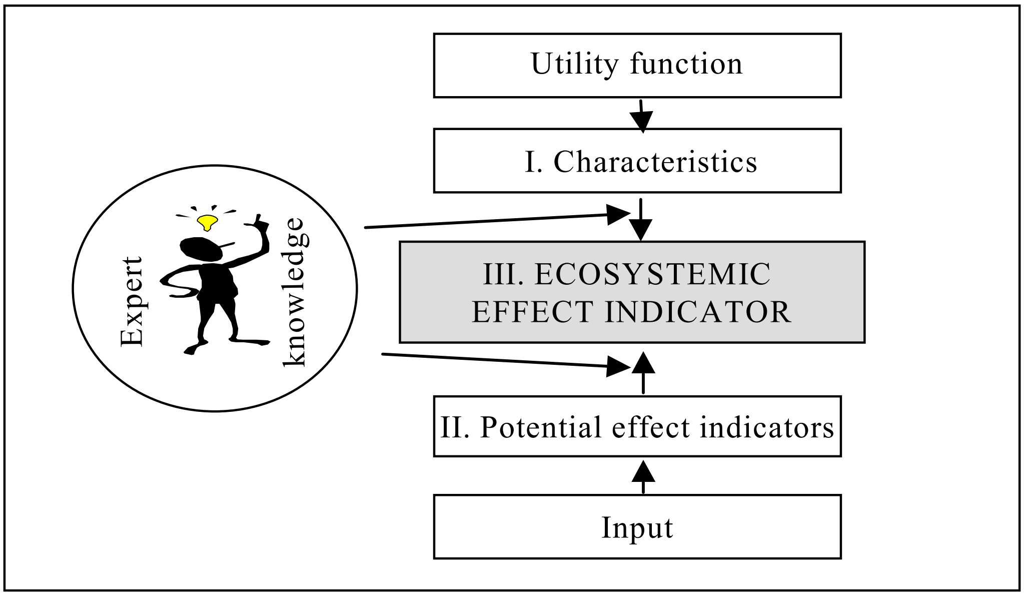


Figure D1: Derivation procedure for ecosystemic effect indicators combining a top-down and bottom-up approach *altered after Merkle and Kaupenjohann (2000a)*

Secondly, one has to select an input, to look at its probable effects, hence to identify the potential effect indicators bottom-up. Thirdly, intersections between I. and II. (figure D1) are determined and EEI are identified by connecting the characteristics of each utility function with the potential effect indicators using expert knowledge (Merkle and Kaupenjohann, 2000a). The decisive criteria for the selection process are mentioned in our definition. The intersection step highly depends on the priority set by the targets.

As advantage of the present approach the derivation proceeding is site-independent. The implementation of EEI, however, will have different expressions at each natural site and therefore requires certain known parameters. Consequently, the data availability is an important supposition. To verify the indicator procedure and to demonstrate what can be a result with location specific peculiarities the approach was tested in an exemplary case study.

CASE STUDY

The data set was collected in the Kraichgau-Region (South-western Germany; Lorenz, 1992). Annual rainfall is 800 mm, average air temperature 9-9,5 °C. Typical soils are haplic luvisols located on plateaus, calcaric regosols on the upper part of the slopes and cambic cumulic anthrosols on the lower end of the slopes. The natural settings regarding texture, aeration and soil water are: loamy silt, bulk density 1,4-1,5 g · cm^{-3}, macro pore volume 40-45 Vol-%, air capacity 8-10 %, available field capacity 15-23 %, pH 6,6-7,5 (Lorenz, 1992). Emissions, releases and the respective input data were descended from a cultivation procedure representative for Triticale. All necessary measures of the chosen tillage system can be gathered from table D1. We focus on soil pressure of the tilling steps.

Table D1: A cultivation procedure for Triticale - example; period considered: one year, field 5 ha

Measure	Season	Number of vehicle passes	Length of tilling time (h · ha^{-1})	Engine power (kW) / weight (t)
Ploughing	autumn	1	1,3	83 / 5,6
Seedbed preparation	autumn	2	0,8	83 / 5
Fertilisation	spring/autumn	4	1 / 0,4	54 / 3,6
Drilling	autumn	1	0,5	52 / 3,9
Plant protection	spring	3	1,1	52 / 3,3
Liming	summer	1	0,2	83 / 4,6
Harvesting	summer	4	2,6	83 / 10
Stubble treatment	summer	1	0,7	83 / 5,4

Classification of emissions and releases and the depending inputs

The classification in view of soil pressure is a periodical, banded impact with short- (concerning plough layer compaction) and long-term (regarding subsoil compaction) effects of mainly local significance. Our case study shows 17 passes by vehicles per year. More than 40 wheel passes may occur in row crops due to more than 10 passes by vehicles (Hakansson and Reeder, 1994). Horn (1999) reported 23 passes by vehicles per year as a maximum in winter wheat. Only 27 % of the area was not overran and 58 % were passed three to six times. Even repeated passes with moderate wheel loads and ground compact pressures may result in deep compaction and persistent negative crop responses (Petelkau and Dannowski, 1990).

Characteristics of the utility functions

The first and second step of the indicator derivation exemplary demonstrate the multitude of feasible characteristics describing ecosystem functioning and accordingly potential effect indicators for the input soil pressure (table D2 and D3). Conceivable effects will predominately impair characteristics at level 0. The characterisation of the utility functions has only to be done once, since it is transferable to other ecosystems.

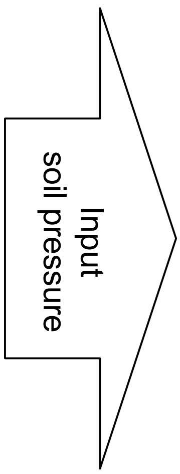
Table D2: Characteristics of the utility functions, level-dependent. Exemplary specified are characteristics meaningful for ecosystem functioning, derived top-down. Compiled after Blume (1992); Brussaard et al. (1997); Doran et al. (1996); Fränzle (1998); Harris et al. (1996); Karlen et al. (1997); White (1997)

Function	**Level II** (relations)	**Level I** (subsystems)	**Level 0** (elements)
Habitat	Food-networks	Nutrient content Consumers pH value Redox potential Predator-prey-ratio	Air-filled porosity Water-filled porosity Macro porosity Mycorrhizal fungi
Transformation	Nutrient cycling	Aeration (air capacity) Biological activity Decomposers Reducers Density/composition of microbial communities	Content/ kind of micro-organisms, above all bacteria Number/kind of fungi, earthworms, insects etc. Available field capacity Respiratory quotient
Filter	Structure	Porosity Peptisation	Pore spectrum Particle size Water-filled porosity Hydraulic conductivity Field capacity
Buffer		Neutralisation Adsorption Desorption Precipitation, Crystallisation	Content of anions, cations Exchange capacity Electrical conductivity Particle size and surface Organic matter Clay content and composition Total surface of active soil particles
Production	Biomass production	Adequate content of nutrient, water, air	Base saturation Pore volume Penetration resistance
Storage	Water cycling	Field capacity	Pore spectrum Pore volume

Potential effect indicators

Since soil compaction strongly affects compartments and whole ecosystems, it has been object of several investigations. Available studies are concerned with effects of soil compaction in general (cf. Soane, 1983) or with special issues. Many analyses were performed on effects on physical properties, e.g., the physical and mechanical parameters of arable soils (Semmel, 1993). Stepniewski et al. (1994) checked effects on soil aeration properties. They present indicators of the soil aeration status. The effects on soil micro structure were investigated (Kooistra and Tovey, 1994) as well as on hydraulic properties (Horton et al., 1994). Brussaard and van Faassen (1994) focused on effects on soil biota and on soil biological processes.

Table D3: Potential effect indicators in view of soil pressure, level-dependent - resumed bottom-up. Compiled after Blume (1992); Brussaard and van Faassen (1994); Dürr et al. (1995); Horton et al. (1994); Kooistra and Tovey (1994); Lipiec and Simota (1994); Soane (1983); Soane and van Ouwerkerk (1994); Stepniewski et al. (1994)



Level 0	Level I	Level II	Function
Macro porosity	Porosity	Structure	Filter
Pore spectrum			Habitat
Pore continuity			Transformation
Pore volume			Production
Field capacity			
Penetration resistance			
Air-filled porosity		Aeration	Habitat
Air capacity			
Earthworms	Decomposers	Nutrient cycling	Transformation
Bacteria			Habitat
Metabolic quotient			Buffer
			Production

Set of ecosystemic effect indicators

The third step of the derivation procedure provides an intersection of the two lists (table D2 and D3) in accordance to each utility function and input chosen. Soil pressure is an input which mainly impacts physical properties. Hence, the indicator set is primarily based on such properties. In table D4 we propose EEI being overlaps as described above.

Table D4: Proposal for an EEI set for the utility functions regarding soil pressure as an input and its principal effect of soil compaction, derived through an intersection of characteristics and potential effect indicators (table D2 and D3). For further details refer to the text

Function	**Ecosystemic effect indicator**
Habitat	Macro porosity+
Transformation	Respiratory intensity and metabolic quotient+
Filter	Pore spectrum, above all the pore volume between 1 and 100 µm*
Buffer	- *
Production	Penetration resistance or macro porosity (depends on the used crop or plant)*
Storage	Field capacity*

+: Decisive regarding plough layer condition
*: Decisive regarding plough layer and subsoil condition
-: For the buffer function there is no EEI with regard to soil pressure

Habitat and transformation are functions predominately determined by the plough layer condition. In contrast, the long-term sustainable productivity and functioning principally depends on subsoil condition. For filter, buffer, production and storage the plough layer as well as the subsoil condition are strongly relevant.

Based on existing scientific knowledge we resumed threshold values and ranges of tolerance as far as known with regard to our proposed EEI (table D5). However, it has to be taken into account that commonly threshold values cannot be directly derived from the scientific data available. Therefore, the setting of thresholds often signifies decisions on the base of value judgements and is subject to considerable uncertainty.

Table D5: Thresholds, standard values and ranges of tolerance, respectively, which are available in literature according to the EEI proposed for soil pressure

Ecosystemic effect indicator	**Threshold/ standard value/ range of tolerance***	**Author**
Macro porosity	15% (> 30µm)	(Cieslinski, 1989)
	10% (> 30µm)	(Dexter, 1988)
Pore spectrum (1-100µm) ≅ cavity volume	10% (very low)	(Blume, 1992)
	40% (extremely effective as filter)	
Field capacity	-	

Ecosystemic effect indicator	Threshold/ standard value/ range of tolerance*	Author
Penetration resistance	1Mpa	(Bengough, 1990; Petelkau, 1980)
	>1,5-3 MPa = 15-30 bar (50% - 0% root growth)	(Horn, 1999)
Air-filled porosity	10%	(Brussaard and van Faassen, 1994; Dürr et al., 1995; Stepniewski et al., 1994)

*: No specification is made for different land use or site conditions
-: No threshold value available

DISCUSSION

Indicator sets have to be suitable to describe the condition of various systems referring to systemic and dynamic aspects of sustainability. Such sets should be independent of specific system conditions. A model-based deduction of indicators will be able to meet this requirement, e.g., based on an analysis of system key functions or elements (Mitchell et al., 1995). The derivation procedure for EEI is deduced from an analysis of significant characteristics according to the procedure described above.

Motivation of indicator proposal and indicator selection

The indicator selection is coined by the difficulty to balance between both high stress specificity and high ecological relevance (Gentile and Slimak, 1992). Despite we have chosen the EEI referring to the following points: i) sensitivity to input, ii) meaningfulness for considered function, iii) spatio-temporal relations, that means short-term reaction but also significance for long-term effects were borne in mind.

Important habitat characteristic for roots, animals and biota among others are represented by the macro porosity. Macro porosity is one of the most directly affected and quick reacting characteristics (Danfors, 1994) and it has a long-term meaning for ecosystem functioning. Stepniewski et al. (1994) suggest air-filled porosity as a suitable indicator for soil aeration, whereas we looked for a characteristic essential for the whole habitat function including enough living space for organisms.

The transformation function, mainly relating to biological processes, depends upon the habitat function. On this account effects are mostly indirect. Investigations of mechanical loading effects on microbial biomass in silty soils (Luvisols) demonstrated a decrease of microbial biomass and an increase of the metabolic quotient, clearly indicating stress (Kaiser, 1992). Microorganisms play a decisive role in matter transformation.

The filter function is primarily based on abiotic properties, predominately on the soil pore system which is strongly influenced by pressure. Hence, a characteristic suitable for that issue is the pore spectrum, chiefly that between 1 and 100 µm (Blume, 1992).

One of the main causes reported for the impediment of root growth by compaction is the penetration resistance which is also affected by soil pressure (Dürr et al., 1995). If the roots cannot penetrate the productivity and yield will be reduced. Penetration resistance is an EEI valid for many plants and crops. Yet, Dexter (1986) discovered that some plant species are able to penetrate into soil aggregates. In these cases macro porosity will be the receptor hindered and therefore the EEI more suitable for the production function.

The storage function is seen as the capacity to store water in this context. The characteristic sensitive to soil pressure as well as meaningful for this function represents the field capacity.

No EEI can be given in some cases. Firstly, if inputs do not impair the characteristics of the considered utility function specifically and significantly no meaningful EEI can be derived. For example, the input soil pressure affects non-chemical characteristics. Hence, for the buffer function as a chemical characteristic we have not detected an EEI. Secondly, if the effects are antagonistic it will also be difficult to mark a decisive indicator. This may require a further development of the method.

Aggregation of EEI

When applying the method to one input in an agroecosystem one may yield various EEI. To reduce the number one possibility is to aggregate the EEI. We suggest the macro porosity as suitable aggregated indicator for soil pressure and its main effect compaction. The condition of the cavity system is essential for plant growth, soil water and soil aeration, cycling and mechanical soil properties (Dürr et al., 1995). The indicator proposal (table D6) demonstrates that macro porosity is directly or indirectly important for filter, habitat, production and transformation function.

The question arises from the aggregation how and whether to integrate normative elements. The diverse EEI for one chosen input may be aggregated to only one or two EEI. Partly this aggregation is possible scientifically based, partly priorities of normative constraints flow in. If one cannot merge these functions on a scientific basis, a weighting of the importance of particular functions is necessary. Further on, it still remains open if an aggregation is useful at all. Ultimately, the indicators obtained imply or reflect both normative and scientific options.

Indicators in relation to threshold values, statements for sustainability or not?

Indicators should have target values that characterise desirable conditions (McCullum et al., 1995). Presently, standardised fixed thresholds referring to our purpose do not exist. Several authors, however, mention target or threshold values which are recommended not to be exceeded (cf. table D5). Related to existing limits in literature the EEI permit statements concerning loading capacities thought to maintain the ecosystem functioning, thus supporting an assessment of the system sustainability. Nevertheless, threshold values vary largely with land use or specific soil functions. Where these values for indicators are lacking they have to be established (Doran et al., 1996). The EEI provide the potentiality to calculate site-dependent loading capacities with available formula (e.g., in DVWK, 1997).

Available threshold values permit to maintain certain characteristics of ecosystem functioning. In turn, these threshold values can be related to current permitted technical limits, e.g., axle loads of agricultural machinery. For instance, Horn (1999) mentions axle loads of 2,5 t and a contact pressure of 50 kPa entailing irreversible soil deformation of silty soils in humid spring. Danfors (1994) recommends that loads to avoid negative effects on single axle units should not exceed 6 t and those on tandem axle units should not exceed 8-10 t.

Transferability to agricultural production

Since EEI predominately address ecosystems they are an essential prerequisite for sustainable agriculture based on unimpaired ecosystem functioning. To provide recommendations for the farmers' practice the EEI have to be transferred into decision aid tools. Restrictions for farmers' tilling methods may be derived from the threshold values of the EEI. These restrictions can have the form of decision criteria. Thereby distinguishable are more qualitative ones, e.g., to establish riparian vegetation or field margins. On the other hand the statements can be more quantitative, e.g., a pesticide amount that must not be exceeded or a soil moisture content that must be at a specific state before tilling.

CONCLUSIONS AND FUTURE TASKS

Our results show that EEI are a promising instrument to assess anthropogenic impacts, especially caused by agricultural emissions, on ecosystems. The examination demonstrated that our site-independent derivation procedure for EEI can be implemented. The EEI yielded may depict diverse peculiarities dependent upon the examined location. Therefore, we conclude that slight modifications ought to be carried out assigned to the investigated ecosystem with its natural settings.

Furthermore our analysis pointed out that in some cases not for every utility function and each input suitable indicators can be derived. But this relates only to unclear or inconsistent effects. We emphasise that an EEI is also not necessarily required in these cases.

Relating the agricultural production system to affected ecosystems the method yields indicators that are important for sustainable ecosystem functioning. In case that threshold values for the selected EEI already exist quantitative statements may enable to assess agricultural production and its effects within the frame of sustainable agriculture.

Vital information about sustainable ecosystem functioning is implicated in the EEI. Applied to the agricultural production system the EEI provide support essential for the development of decision aid tools for farmers.

To reduce the number of EEI (for one ecosystem concerning various inputs) an aggregation for several inputs is possible. The case study performed has outlined that macro porosity may be an aggregated EEI for an agroecosystem with regard to soil pressure.

Three main tasks of further research should to be treated: (1) other inputs, (2) another ecosystem, and (3) a further target of preservation. (1) Presently, we work on EEI for a pesticide chosen and the nitrogen fertilisation. We plan to consider the effects of heavy metals, e.g., cadmium contained in fertilisers and to derive EEI for this concern. (2) Subsequently, efforts should be forced to derive EEI for adjacent ecosystems keeping the fact in mind that for such ecosystems EEI have to handle with the scale issue. This issue eventually implicates adaptations of the method to other realities. Thus, the approach will be applied to a close to nature ecosystem. The focus of this issue will be which spatio-temporal dimension of indicators is suited to assess sustainable agriculture. (3) Moreover, we will test the applicability for other targets, e.g., species preservation to consolidate the indicator derivation method.

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E APPLICATION OF ECOSYSTEMIC EFFECT INDICATORS WITH REGARD TO CADMIUM AND CARBENDAZIM IN AGRICULTURAL SYSTEMS - FOCUSSING THE TEMPORAL SCALE

ABSTRACT

Ecological impact assessment essentially contributes to an evaluation of the sustainability of agricultural systems. However, the temporal dimension of this assessment is mostly lacking. An indicator approach providing ecosystemic effect indicators to support an impact assessment of agricultural production on ecosystems was evaluated. One major aim of the present study was to test this indicator approach for material inputs which result from agricultural emissions and finally cause effects in surrounding ecosystems. Furthermore, temporal aspects should be integrated into indicator derivation. As sample substances the fungicide carbendazim and cadmium contained in P-fertilisers which show effects on different times scales were selected as substances to be examined in a case study. The case study was conducted at the University of Hohenheim, Stuttgart. The used data set was collected in South-Western Germany. This study showed that it is realistic to base the derivation procedure on "main functions of ecosystems". The indicator derivation included the following steps: In a first step the agricultural emissions were classified according to the criteria scale, scope and balance. Following the indicator development was performed: Firstly, utility functions of the ecosystem were deduced. The essential processes and elements were defined. Secondly, receptors of impacts sensible to cadmium and carbendazim were identified and compiled. Finally, the ecosystemic effect indicators were identified by overlapping characteristics of the functions and receptors. As a major result two sets of ecosystemic effect indicators are presented in this article: first for carbendazim which mainly causes effects on a short-time scale and second for cadmium whose effects occur on a longer time scale. This examination showed that an integration of the temporal dimension is suited to facilitate the indicator selection.

INTRODUCTION

Ecosystems are complex systems exposed to a multitude of stress and impacts. To assess agricultural management systems, e.g., in the context of sustainability, all impacts resulting from agricultural production on ecosystems have to be evaluated. However, the evaluation of environmental impacts of agricultural production still remains critical because of the (1) manifold types of emissions and inputs occurring and (2) different temporal and spatial scales of impacts which vary to a great extent.

Impact assessment in ecosystems has to consider different hierarchies: organisational, spatial and temporal hierarchies. The processes interconnected within the organisational hierarchies depend on the various spatial and temporal levels (de Kruijf, 1991). Currently, spatial dimension is often included in ecological impact assessment, e.g., Wiens (1989); Haila (1998). Whereas the temporal dimension is only rarely regarded (von der Wiesche and Werner, 1998). Even though the dimension of time provides an essential access for systemic considerations in ecology (Kümmerer, 1997).

In the present study, the assessment of agricultural systems and their impacts is based on an indicator approach as previously developed (Merkle and Kaupenjohann, 2000a). Within this concept utility functions of ecosystems (de Groot, 1992; Fränzle et al., 1993) represent the starting point of indicator derivation. The derivation method for indicators has been verified for the impact due to soil pressure (Merkle and Kaupenjohann, 2000b). From the big number of potential receptors which have to be assessed the most important ones have to be extracted. Therefore the first step is an analysis of relevance. The criteria scale (length of space-temporal effect chains), balance and scope are decisive for this analysis. The emissions[1] and resulting inputs[2] are classified for the estimation of relevance according to the following aspects: i) kind and type of emitted substance, ii) its transport/transformation and iii) its potential impact in affected ecosystems. Emissions could travel very fast from a source to a sink or they need a long time. Accordingly, reactions and effects in adjacent ecosystems can vary to a great extent regarding time and space distances. Therefore, a classification and an estimation of relevance of agricultural emissions represent a suitable prerequisite for the test of the indicator approach. Thus we define types of emissions and impacts expressing frequency, mobility, persistence of

[1] Emissions include material and non-material releases of the agricultural production system, e.g. nutrients, soil pressure, NO_x etc. Harvest goods are not included.

[2] Inputs include energy or matter emitted by the production system, e.g. nutrients, pesticides and heavy metals which reach an ecosystem.

substances and initiating various effects. Categories potentially affected by inputs are: toxicity, equilibrium (nutrification, acidification) and biodiversity.

It is the major aim of this study to apply the indicator approach to material impacts. In summary the objectives are:

(1) to test the applicability of the indicator derivation method previously developed for material emissions of the fungicide carbendazim and of cadmium, which is mostly contained in P-fertilisers, and their corresponding effects in agroecosystems in a case study,

(2) to show and apply an approach to classify emissions and to analyse their relevance by the example of emissions resulting of producing Triticale (*Triticosecale Wittmack*) as an energy plant,

(3) to integrate temporal dimensions into the consideration. To evaluate the effect of potential stressors on ecosystems it is proposed to identify the accordance of stress dynamics (emissions) and highest sensitivities of receptors on similar temporal scales.

IMPACTS OF AGRICULTURAL PRODUCTION ON ECOSYSTEMS

The evaluation of impacts on ecosystems demands the definition of a goal where aims and assumptions are clearly named. The ecosystemic effect indicator approach is based on targets and values which are assigned to utility functions of ecosystems (Doppler, 2000). The term utility functions (de Groot, 1992; Fränzle et al., 1993) of ecosystems covers the soil functions habitat, production, storage and the regulation function which is subdivided into the filter, buffer and transformation function. By reflecting the basic capacity of the soil to function (Herrick, 2000) these functions have to be maintained on a long-term scale.

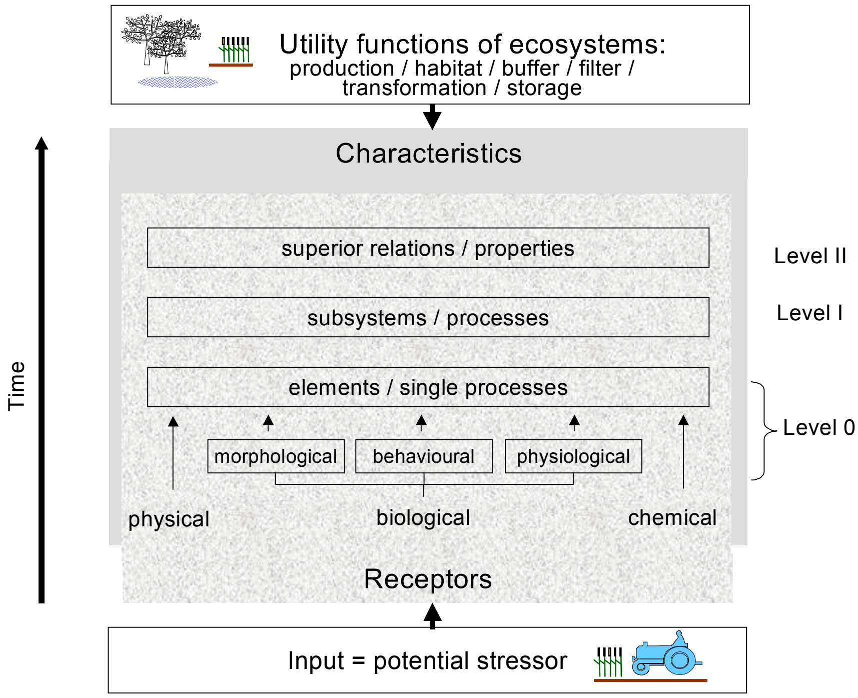

Figure E1: Utility functions of ecosystems and their characteristics and receptors which are level-dependent. The receptors may differently be affected by inputs dependent upon time

Inputs may affect receptors of an ecosystem (figure E1). Effects caused by emissions of agricultural production may immediately emerge. Reactions on a short-term scale represent behavioral, physiological or morphological responses (figure E1). For instance, if a high dose of a pesticide reaches the topsoil at certain points it may hurt soil-organisms. Results may be, e.g., an upset of predator-prey balances. But effects may also occur with a time delay, that means on a middle- or long-term-scale, e.g., alterations of system equilibrium through substance accumulations or reactions of receptors like communities or relations between subsystems. This may cause alterations at higher hierarchical levels. Thereby the entities at the highest hierarchical level imply slow time constants, whereas the lowest levels (figure E1) are characterised by quick time constants (Müller, 1992; Ulrich, 1994). If the stress resulting from an input is severe it may also directly affect receptors of the level of subsystems or even of superior relations and properties (figure E1).

Temporal scales and long-term considerations

Even though relevance of time is acquainted (SRU, 1994) deficits exist between requirements and reality in ecosystem research. The time horizon of measurements or examinations often notably differs from the time scales required for an adequate evaluation of the results (Kümmerer, 1997). For instance, ecosystem research frequently aims at time scales of one to several centuries but it carries out experiments at short time scales from seconds to a few years. If the manifoldness of time scales, their interactions and interdependencies in evaluation studies are not regarded the consequences of impacts are only incompletely gathered (Kümmerer and Held, 1997a).

Conforming to Levine and Knox (1994) and Frede et al. (1994) short-term is defined as hourly to seasonal, middle-term as years to decades and long-term as decades to centuries (figure E2). Ecotoxicology provides widespread information on acute toxicity of various substances (on a short-term scale). Examinations which aim at a middle-term timeline are rare, however (von der Wiesche and Werner, 1998). Also, in the field of long-term effects many gaps appear (Blume, 1992; Wagenet, 1998). Notwithstanding, impact assessments with the background of sustainability imply the consideration of all time scales: (1) acute effects, (2) effects occurring on middle-term scales and (3) effects appearing after long time.

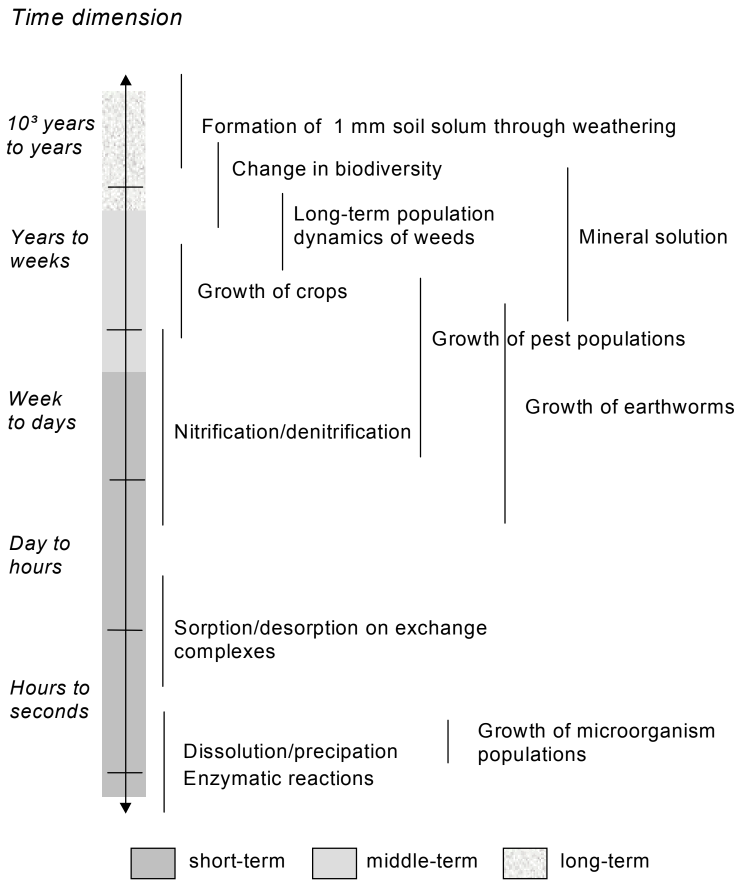

Figure E2: Potential receptors (processes) of inputs in agroecosystems, their temporal dimensions and the time scales of consideration. Data used from Edwards and Bohlen (1996); Frede and Bach (1997); Lenz (1995); Richter et al. (1996); Sparks (2000)

Persistence and toxicity

Persistence a central criterion for the evaluation of substances (Klöpfer, 1994) and toxicity of substances are criteria which need to be considered in conjunction with temporal aspects. Persistence is defined as the property of substances which is chemically stable versus influences and forces of the environment. The persistence of substances can be quantitatively described through its half-life period or concerning gases through its medium atmospheric lifetime (Hulpke et al., 1993, p. 540). The duration of impacts resulting from emissions depends on the persistence of the substance. With respect to toxicity the terms acute and chronic are commonly used to define the toxicity of a substance along with the duration of an impact.

Time dependency of effects

Not only the characteristics of the harmful substances are decisive for effects but also at which time an impacting substance hits a certain ecosystem. The resulting effect mainly depends on: (1) on the emission side i) point in time (Dahlin et al., 1997), ii) concentration, intensity of impacting stress, iii) potential duration of impacting stress, as well as iv) substance properties like mobility or toxicity. For instance, some substances may only impact ecosystems during one vegetation period, e.g., the active substance Isoproturon causing acute effects. Several substances or impacts actively react or influence the system more than one production cycle, e.g., nitrogen or soil pressure. (2) On the ecosystem side the sensitivity of the receptor expresses how rapidly or how intensely the ecosystem may be influenced by stress (Holling, 1986).

The sensitivity of the receptors for impacts depends on season related factors (Schubert, 1991). The altering sensitivity of receptors within a year (cf figure E4) as well as the time delays of direct (e.g., death of organisms after application of pesticides) and indirect (e.g., a slower matter decomposition) effects are factors highly important with regard to the temporal dimension. For instance, if the input affects the juvenile state of an organism the harm caused will have a deep scope. Furthermore, sensitivity and elasticity of a system depend on the system history, e.g., time, duration and kind of preceding loading (Kümmerer and Held, 1997b).

Ecosystemic effect indicator approach

To evaluate the impacts caused by agricultural production an indicator approach has been developed (figure E3; Merkle and Kaupenjohann 2000a). This approach includes as a first step a classification of emissions and impacts in considering time aspects. All following steps of the derivation approach should also show relations to time features: Step one: Compilation of a list with level-dependent characteristics of each utility function for the ecosystem considered (top-down). Step two: Compilation of a list with receptors for a certain input (bottom-up). These receptors represent potential effect indicators. Step three: Overlapping of the two lists and identification of the specific ecosystemic effect indicators (EEI) by means of expert knowledge. A simplification of step three arises through the integration of temporal aspects: decisive is when the impact affects a sensitive process or element. Furthermore, the EEI selection is oriented on the goals and the indicator requirements defined at the beginning of the examination.

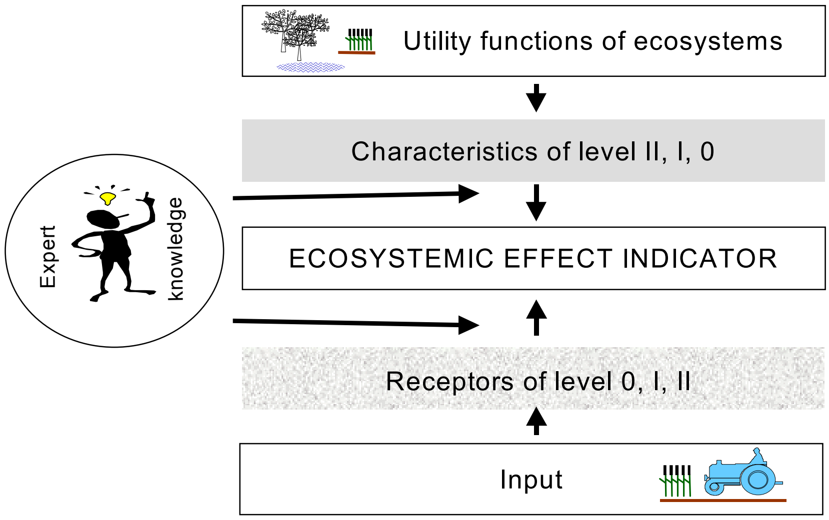

Figure E3: Procedure for the derivation of ecosystemic effect indicators. *Modified after Merkle & Kaupenjohann (2000a)*

CASE STUDY

The production of Triticale as an energy plant (Lewandowski et al., 1999) is investigated in the exemplary case study. Data for this conceptual case study originated from studies of the "Sonderforschungsbereich No. 183" (Lorenz, 1992; Zeddies, 1995). The emissions and the respective input data descend from a cultivation procedure representative for Triticale (Diekmann, pers. com.; Merkle and Kaupenjohann, 2000b). Data concerning effects are drawn out from literature. The databases include laboratory toxicity tests and field studies evaluating multiple end-points of biological hierarchy.

We check the relevance of impacting substances before the EEI derivation. The proceeding starts with an inventory analysis according to the life cycle impact assessment (LCIA; SETAC, 1993). Similar to the classification step of LCIA data of emissions and inputs from the inventory analysis are grouped into several effect categories. The effect assessment characterises the relationship between the intensity of exposure to an agent and the magnitude of ecological effects (Cairns, 1998).

Relevant emissions are preselected according to their potential toxicity (low, middle, high), persistence and frequent use in a second step. In the present study, we preselected two relevant potential stressors: the fungicide carbendazim and the heavy metal cadmium. Carbendazim has been selected as exemplary substance since fungicides are generally highly toxic to earthworms. Special interest is laid on heavy metals because of their inherent persistence.

Carbendazim (= methyl benzimidazol-2-ylcarbamate) is frequently used against fungal diseases in wheat. The active compound shows a persistence of up to 230 days in agricultural soils (Domsch, 1992; Chemistry, 1994; Perkow and Ploss, 1999). Therefore, a consideration of Carbendazim is important. Carbendazim has been identified as chemical stressor especially for the soil fauna in laboratory tests (Römbke and Federschmidt, 1995; van Gestel et al., 1992; Paoletti, 1999) microcosm studies (Förster et al., 1996) and field experiments (Eder et al., 1992; van Gestel, 1992).

Cadmium tends to accumulate in the topsoil after application (Mortvedt and Beaton, 1995). Heavy metal contaminants may disturb soil ecosystems, e.g., by affecting the structure of soil invertebrate populations (Spurgeon et al., 1995). Further, adverse effects on animal health have been detected (Thornton, 1992) and cadmium may even influence human health (Mortvedt, 1996).

Classification of cadmium and carbendazim emissions in agroecosystems

To outline which temporal scales are affected and to judge the importance of the emission the emissions are assessed by an analysis of matter balances. Where data derived from matter balances is lacking we at least aim at a qualitative classification in a catalogue and an evaluation of the appearance probability.

Sources of cadmium in agroecosystems

Generally employed commercial phosphate fertilisers contain small amounts of heavy metal contaminants derived from the phosphate rock (Mortvedt, 1996). Close relationships exist between concentrations of phosphate and cadmium in superphosphates and the sources of phosphate rock (Williams and David, 1973). Phosphate rocks always contain cadmium, although concentrations vary widely from < 1 mg · kg^{-1} to > 100 mg · kg^{-1} (Richards et al., 1998). The typical applications of phosphate in Western Europe involve annual additions of 2 - 5 g Cd · ha^{-1} (Gunnarson, 1983). Mortvedt and Beaton (1995) state that 3,3 g Cd · ha^{-1} are applied with 20 kg P · ha^{-1}.

We assume in our case study that 160 kg · ha^{-1} basal dressing are added once every three years including Triple superphosphate which contains 25 – 30,6 mg Cd · kg^{-1} (Wilcke and Döhler, 1995; Biomasse, 1998). However, it is difficult to estimate accumulations of cadmium applied with phosphate fertilisers since mechanisms for removal and addition cannot be easily assessed (Mortvedt and Beaton, 1995).

Concerning the temporal effects it is mentioned that cadmium in phosphorus applications may have short- and long-term impacts with regard to cadmium phytoavailability. Plants generally take up only 1 - 5% of the soluble cadmium added to soils (Grant et al., 1998). Parts of the soluble cadmium can be leached or absorbed by organisms. Moreover, nitrogen fertilisers may increase cadmium uptake of plants, although the fertiliser does not contain significant levels of cadmium. This may be due to soil acidification, increases in osmotic strength of the soil solution or ion exchange reactions (Grant et al., 1998).

Sources of carbendazim in agroecosystems

In the present case study, one fungicial treatment of Triticale is suggested using carbendazim (applied as DEROSAL, Hoechst AG, 360 g a.i. l^{-1}) at the recommended application rate of 0,18 kg a.i. ha^{-1}.

The application process itself represents the main source of carbendazim within the Triticale production system. During the annual field application, the initial compound directly reaches plants, topsoil and atmosphere. A second important source of carbendazim and pesticides in general is the handling process at the farm yard during the preparation and cleaning of the spraying equipment (Thorstensson and Castillo, 1997). Since farm yard gravel offers only unfavourable conditions for biodegradation and adsorption, the spilled pesticides easily penetrate into surface and groundwater. However, it is impracticable to include carbendazim emissions from spillage in the present case study because quantity as well as frequency of this source of pesticide emissions may not be determined.

The toxicity of the fungicide is strongly dependent on its persistence. Since carbendazim degradation is lower in soils with high pH and high clay content (Liu and Hsiang, 1994), the toxic potential of the compound is higher in these soils. In general, the stability of carbendazim does not exceed one year (Perkow and Ploss, 1999). Since the half-life of the compound does not exceed 230 days (DT 50 in soils 50-230 days depending on soil conditions; Domsch, 1992), we expect no accumulation of the compound in agricultural soils over the years. Therefore, the assessment of carbendazim impacts on agro-ecosystems remains restricted to a time scale of one year or one crop rotation, respectively.

On the basis of a classification, the emission may be ranked regarding their potential effects and impacts. Emission criteria of the classification may be gathered of table E1:

Table E1: Categories of the material emissions carbendazim and cadmium and their exposition

Category		**Carbendazim**	**Cadmium**
Source of emissions	Production (of the substance used)	(X)	X
	Product application	X	X[1)]
Temporal aspects of emission	Unique[2)]	X[3)]	
	Periodical	X	X (P-fertilisation)
	Continuous		
	Time of application	June	September
Spatial kind of source	Point	(X)[3)]	
	Banded	(X)	
	Area	X	X
Emission properties	Volatility	medium	low
	Water solubility	low	low
	Persistence	medium[4)]	high
Exposition/	**Water/soil**:	X	X
process of transport	solution	X	X
	particle bounded	X	X

Category		Carbendazim	Cadmium
	Air:	X	X
	gaseous	X	
	particle bounded	(X)	X

1) Contained in inorganic fertilisers

2) Depending on the duration of observance

3) Point emission occurring at filling or cleaning of plant protection equipment

4) T 90 in soils < 365 days (Domsch, 1992; Perkow and Ploss, 1999)

(X) Of secondary importance

Classification of cadmium and carbendazim inputs in agroecosystems

The input pathway and the input amount as well as substance dispersion and substance persistence primarily influence the external exposition (Fränzle, 1998). Emissions are transported and transformed. The emitted substance which arrives in an ecosystem represents an input which cause potential effects. The agroecosystem represents at the same time site of emission and site of potential effect for cadmium and carbendazim.

Both pesticides and fertilisers predominately attain the topsoil at first where most of the soil organisms live (Frede and Bach, 1997). As a consequence, especially these organisms are firstly mared and the depending functions are strongly affected. Since the EEI derivation in this investigation remains concentrated on the soil system, a worst case scenario is assumed where the whole quantity of substance applied attains the topsoil (4 – 4,8 g cadmium $\cdot$ ha^{-1} $\cdot$ a^{-1}, 0.18 kg a.i. carbendazim $\cdot$ ha^{-1} $\cdot$ a^{-1}). Major exposure route of cadmium to receptors is via pore water (Umweltbundesamt, 1998). Following, all receptors which are in contact to the pore water might be affected.

Temporal scales of effects regarding Cadmium and Carbendazim

The temporal scale of potential effects notably differs. For instance, the input of cadmium may affect receptors on a short-term scale (table E2), e.g., high concentrations of cadmium decrease the respiration of soil microorganism populations (Lepp, 1981; Williams and Wollum, 1981). Or the activity of cellulase, phosphatase, amylase and nitrogenase descents (Blume, 1992; Williams and Wollum, 1981). More frequent, however, effects occur after a middle- or long-term period (Semu and Singh, 1996) because of the cadmium accumulation over time. Enrichment of this metal in plants, e.g., legumes or crops may be a feasible consequence (Guttormsen et al., 1995). An enhanced cadmium concentration entails a greater time-dependent hazard of harmful effects on animals, plants and humans. Effects may appear after having reached the damage threshold. Accordingly, the input of cadmium in agroecosystems requires a long-term consideration. However, information on long-term effects of cadmium in field are rare. Particularly, the corresponding thresholds are not known (Blume, 1992).

The input of carbendazim in agroecosystems shows fast reactions of receptors (table E2). The effects are mostly immediately initiated that means being acute ones. Since the half-life of the compound does not exceed 230 days (Domsch, 1992) the time of consideration for carbendazim effects should be concentrated on the short-term scale (table E2).

Table E2: Temporal criteria of effects for the material inputs carbendazim and cadmium

Category		**Carbendazim**	**Cadmium**
Time scale of effect	short-term	X	(X)
	middle-term	(X)	X
	long-term		X

Resumed primary effects of carbendazim belong to the short-term scale whereas graver effects of cadmium are expected on middle- or long-term scales.

Ecosystemic effect indicators for the inputs Cadmium and Carbendazim

The first step of the EEI derivation was the characterisation of the utility functions (figure E3). A list of feasible characteristics was derived for each function (Merkle and Kaupenjohann, 2000b). The second step was the compilation of receptors, the potential effect indicators, for the inputs of cadmium and carbendazim.

Potential effect indicators

A broad spectrum of effects in agroecosystems caused by cadmium arises (table E3). Cadmium effects in soils can depend on soil properties like texture, humus content and pH. Earthworms are suitable receptors for assessing the impact of heavy metals because of their limited mobility (Paoletti, 1999). Peregrine earthworms may rapidly respond when a heavy metal impact occurs (Doube and Schmidt, 1997). Earthworm acute toxicity tests in laboratory experiments revealed that cadmium affects earthworm reproduction and this influences population dynamics (Spurgeon et al., 1995). Furthermore, the cocoon production of earthworms is sensitive to cadmium (van Gestel et al., 1992). In the field, earthworms feed on solid soil constituents and therefore accumulate pollutants, e.g., cadmium (Lee, 1985). Earthworms accumulate cadmium up to an enrichment factor of about 11 - 22 (Domsch, 1985). Besides the fauna, enrichments in flora of about 12 - 18% (leaf tissue and roots) were found (Blume, 1992; Grant et al., 1998; Lepp, 1981). Generally the pollen and the stigma are sensitive to a surplus of cadmium. Low cadmium concentrations in the stigma may hamper the growth of pollen (Schüürmann and Markert, 1998, p. 609).

Effects of carbendazim are characterised by a selective impact on specific receptors (table E4). Especially the number and biomass of enchytraeids and juvenile earthworms is affected by carbendazim (Förster et al., 1996; Römbke and Federschmidt, 1995; van Gestel et al., 1992). The respective effects on litter decomposition and mineralisation in soils are of particular interest. They influence fertility and aeration of soils and therefore the availability of nutrients and oxygen to primary producers (Coleman and Hendrix, 1988). Effects of carbendazim on unspecific soil biology parameters, e.g., SIR-microbial biomass, urease activity and soil respiration could not be proved (Förster et al., 1996; Lampe and Aldag, 1979; Nowak and Hurle, 1984). In table E3 and E4 potential effect indicators for the material inputs of cadmium and carbendazim are summarized.

Table E3: Examples of potential effect indicators and their meaningfulness for higher organisational levels with regard to the input of cadmium, compiled bottom-up. Data used from Blume (1992); Grant et al. (1998); Lee (1985); Lepp (1981); Umweltbundesamt (1999); van Gestel et al. (1992); Williams and David (1973); Williams and Wollum (1981)

Level 0 (elements/processes)	**Level I** (subsystems)	**Level II** (superior relations)	**Function**
Biomass of earthworms Biological activity of microorganisms	Decomposition	Nutrient cycling	Transformation
(Diffusion into) sesquioxide particles Formation of Cd-Chloride-Complexes Cd^{2+}-leaching (pH<5,5)	Ion exchange capacity	Ion exchange	Buffer
Biological activity of microorganisms (cellulase, phosphatase, amylase, nitrogenase activity in microorganisms) Reproduction rate of earthworms	Assimilation Decomposition	Nutrient turnover Biomass production	Production
Ratio of actinomycetes/bacteria Cocoon production of earthworms Cd-accumulation in plant individuals Respiration of microorganisms	Predator-prey-ratio	Food-chains/-webs	Habitat

Table E4: Potential effect indicators and their meaningfulness for higher organisational levels with regard to the input of the fungicide carbendazim, compiled bottom-up. Data used from Eder et al. (1992); Förster et al. (1996); Khan et al. (1987); Römbke and Federschmidt (1995); van Gestel et al. (1992)

Level 0 (elements/processes)	**Level I** (subsystems)	**Level II** (superior relations)	**Function**
Earthworms (number and biomass of juveniles) Fragmentation of organic matter Humus content and kind Humin substances	Decomposition	Nutrient cycling Food-chains/-webs	Transformation

Level 0 (elements/processes)	**Level I** (subsystems)	**Level II** (superior relations)	**Function**
Ammonification	Nitrogen turnover	Nutrient cycling	Production
Nitrifying organisms		Biomass production	
Ammonifying organisms			
CMCase	Decomposition	Food-webs	Habitat
		Nutrient cycling	

EEI identification with regard to time relations

The temporal aspect is recognised as an additional aspect which must not be ignored in facilitating the indicator selection. Therefore, we propose to arrange the temporal heterogeneity of receptors' sensitivities as well as the dynamics of emissions and inputs occurring and to look for intersections on similar temporal scales (step three of the indicator derivation). The farmer applies carbendazim in late spring (figure E4). Potential receptors for this fungicide may be elements like earthworms, especially their cocoon production and their reproduction behaviour (table E4). The sensitivity of the earthworms is highest in spring when the main time of reproduction takes place (figure E4). To identify an EEI representative for the input of the fungicide carbendazim and, e.g., the habitat function requires regarding intersections between the time frame of stress impact (June) and process sequence or high sensitivity of the receptor potentially affected (earthworm reproduction). The number of juvenile earthworms (table E5) results as EEI for the example mentioned. Filser (1995) observed similar effects in her examinations of the influence of fungicides (with copper) on Collembola. It was essential to look at times with highest receptor sensitivities in identifying the indicators most suitable for this definite input.

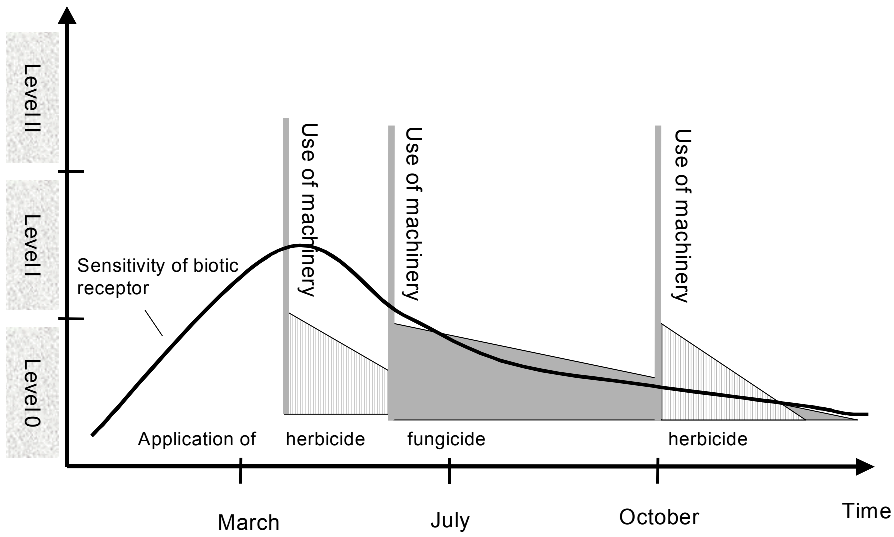

Figure E4: Frequency of inputs in an agroecosystem, portrayed by the example of pesticide applications, and the sensitivity of potential receptors, portrayed by the example of earthworm reproduction. Danger of harm is higher when reproduction proceeds. Impacts trace on diverse levels

Cadmium represents an input which primarily influences the agroecosystem by accumulation on a middle- or long-term scale. However, searching an EEI representative for accumulated cadmium in agroecosystems signifies not necessarily a long-term process (table E3, E5). In fact, a characteristic located on a low hierarchical level of short reaction time may be the indicator most suitable, e.g., the biological activity of microorganisms. It ensues as a result that both the emergence of an impact (long-term) and the reaction of a receptor (immediately, time-delayed) often are but must not necessarily be located on a corresponding scale.

Table E5: EEI sets for the utility functions of ecosystems regarding cadmium and carbendazim as inputs, developed by an intersection of the characteristics and potential effect indicators

Function	**EEI - Cadmium**	**EEI - Carbendazim**
Habitat	Ratio of actinomycetes/bacteria Cocoon production of earthworms Respiration of microorganisms	Number of juvenile earthworms or reproduction rate of earthworms or cocoon production of earthworms
Transformation	Biomass of Earthworms (especially of *Dendrobaena veneta, Lumbricus terrestris*)	Biomass of earthworms and enchytraeids
Filter	-	Number and distribution of macropores*
Buffer	With Cd occupied ion exchange sites	Humus composition
Production	Biological activity of microorganisms (cellulase, phosphatase, amylase, nitrogenase activity in microorganisms) Reproduction rate of earthworms	Biomass of earthworms and enchytraeids
Storage (concerning water and nutrients)	-	Humus composition

-: A direct EEI cannot be identified with regard to carbendazim and cadmium

*: Indirect EEI

DISCUSSION

The present case study showed that the EEI derivation method is also suitable for material inputs in agroecosystems. Therefore, the EEI derivation method represents a powerful tool to develop transferable indicators for environmental impacts in a site-independent manner. The yielded EEI, however, are location specific adapted. They can depend on the site, the agricultural production system and the respective emissions. To be interpreted the EEI have to be seen in the context they were deduced. The derivation process stands out as highly transparent. Therefore, it is easy to comprehend by different target groups like scientists or landscape planners. The users can alter or upgrade the lists obtained in step two of the derivation procedure according to their specific task in case of applying the EEI to other questions or integrating new research results. Subsequently, step three of the derivation procedure has to be adapted. Thus, similar to a location specific parameterisation the planners themselves are allowed to derive problem oriented indicators.

The implementation of the methodological approach for material inputs by the example of toxic substances illustrated that careful attention should be paid to temporal aspects. The examination of cadmium impacts raised the problem of substance accumulation over time. Indicators have to be identified with long-term meaningfulness which are, however, short-dated sensitive in this case. This is enabled by compiling temporal aspects of stress appearance and by taking into account the varying sensitivity of potential receptors for specific inputs. Subsequently, intersections such that characteristics of similar temporal and organisational scales cross are looked for. However, in some cases such a cross may not be possible.

Innovations of the developed indicators compared to existing approaches

EEI go beyond existing indicators in so far as they not only indicate effects but also integrate a direct reference to functions and functioning of ecosystems. As yet, effects on ecosystem functions usually are assessed by studying the functions themselves. There can be indicators for subsystem functions as well as for the whole ecosystem functioning (Rapport, 1998). Or effects are assessed by looking at appropriate endpoints of impacts for whom indicators are needed (Weeks, 1998). The question of how to extrapolate effects which occur at one level to impacts at a higher hierarchical level still remains critical (de Kruijf, 1991). Frequently, the EEI are settled on the level of elements but integrate meaningfulness for higher organisational levels. With respect to the varied inputs the possibility was realised that for two distinct inputs and one ecosystem function the same EEI may be identified (table E5). Harris et al. (1996) examined soil quality with the assumption that all soil quality and health indicators must address one or more of the functions of soil quality. The authors confirmed that some indicators occur in different biological, physical or chemical categories. These indicators support the same function whereas some indicators occur in the same category supporting distinct functions.

Assessment of agricultural production

To perform an assessment of agricultural production, e.g., with the background of ecological sustainability the EEI may be related to existing threshold values. This implies giving quantitative information to the agents about the toxicity of a substance or potential effects. It is possible to relate the EEI to current threshold ranges. Present databases contain results from toxicity tests of risk hazard assessments. For instance, for carbendazim and the corresponding EEI of the transformation function quantitative toxicity data can be found as follows: (1) for litter decomposition by Enchytraeids the $NOEC_{50}$ (field) is 0.24 mg · kg^{-1} (Römbke and Federschmidt, 1995). (2) The production of fertile cocoons (earthworm) as EEI of the habitat function has an EC_{50} of 1.92 mg a.i. kg^{-1} (dry soil; van Gestel et al., 1992). Threshold values for cadmium have to include soil properties. These properties may partly exert an influence on feasible effects of cadmium, e.g., clay soils may absorb more cadmium. Precaution values derived on the basis of ecotoxicological data (pH > 6) for the habitat function in clay of 1.5 mg · kg^{-1}, in loam of 1 mg · kg^{-1} and in sand of 0.4 mg · kg^{-1} are found in the literature (Schütze, 1998). Such data may provide the basis for threshold values. At present, however, laboratory data are frequently employed to give statements concerning limits. Such laboratory data should be supplemented with field examinations on a larger scale. Another possibility may be a simulation, e.g., the model based deduction of limits, for instance, critical loads (Gregor et al., 1996). However, such values only are available for nutrifying and acidifying substances and often are rough (Zak et al., 1997). Basic approaches to derive critical limits for ecosystems are available for heavy metals (Umweltbundesamt, 1998). Quantitative thresholds will enable a final evaluation and facilitate the implementation of sustainable agriculture. However, further research is needed that focuses on methods to deduce guidelines for scientifically based threshold limits. When these become available on a large scale the EEI can be related to these limits and ultimately evaluated.

Further, from this investigation it can be deduced that EEI provide the basis for aiding decisions regarding the application facilities with respect to farmers. Indicators for the evaluation of environmental impacts resulting from agricultural production are rarely available (von Wirén-Lehr, 2000, in press.). In this approach, special focus of the assessment is laid on ecological aspects. The EEI integrate ecosystemic knowledge and thus the deduction of helping make recommendations that are ecologically based is supported. Such recommendations may be to avoid carbendazim applications at times when the earthworms are most active in their reproduction process. Another suggestion may be to use Thomas phosphate with small traces of cadmium instead of Triple superphosphate. Considering such recommendations allows farmers to produce on a long-term scale and to maintain the sustainability of their agroecosystem.

Drawbacks of the approach

As to an ecological impact assessment based on EEI the following drawbacks appeared: Firstly, it is critical to specifically assign effects to specific inputs. On the one hand interactions and/or antagonistic effects between various inputs may occur. For example, antagonistic interactions of cadmium with zinc are documented (Lepp, 1981; Umweltbundesamt, 1999). The addition of zinc degrades the absorption of cadmium by the flora (Grant et al. 1998; McLaughlin et al. 1995). On the other hand exact cause-effect relations cannot be assigned because of time delays of effects caused by accumulations or a high background noise. This coincides with effects for whom the initiator could not unambiguously be determined, e.g., certain effects may be caused due to natural oscillations as well as due to human impacts. Regarding cadmium the input specificity of the EEI is sometimes difficult to assign. Moreover, the indicator selection may be difficult in cases where both a high sensitivity for a specific input and the meaningfulness for ecological functioning on the other hand should be complied (Gentile and Slimak, 1992).

Secondly, sustainability assessment with an approach only based on indicators remains incomplete. Quantitative statements are needed for an evaluation and subsequent implementation of agroecosystems. However, the current research gaps concern two different issues: (1) Available limits or threshold values are often derived on the level of elements. The higher the hierarchical level the more difficult the deduction of the threshold value will be and the depending force of expression gets more imprecise. (2) If, up to now an effect of a substance is incompletely documented or the receptor most suitable is not detected, no thresholds can be determined.

CONCLUSIONS AND FUTURE TASKS

The EEI identified with the derivation procedure supply information for scientists as well as for planners. If the relation to threshold values succeeds the EEI will espouse quantitative impact assessments within the frame of sustainable agriculture. The application revealed that the EEI approach can be deemed to be a powerful tool to enable an ecological impact assessment of agricultural production. The methodological approach for the derivation of indicators gathers effects which are already known. Thus at the present time no statements can be given with respect to effects not yet documented. In principal, however, new research results may easily be integrated into the approach.

Further the application of the EEI derivation method showed that an estimation of relevance of emissions and inputs depending upon defined criteria is a suitable prerequisite to facilitate the derivation of EEI.

The study demonstrated that the indicator derivation approach may be reasonably enlarged by integrating time aspects. Examining the material inputs cadmium and carbendazim was suited to temporal features.

One has to consider that in systems on large scales mono-causal connections between cause and effect may rarely be identified in applying the method on adjacent ecosystems as a next step (Kümmerer and Held, 1997b). The off-site effects which emerge at endpoints spatially away from the agroecosystem need further research. Temporal delays play an important role for adjacent ecosystems, e.g., lakes. Clear endpoints of effects depending on one input are rarely expected the larger the examined systems are in time and space. These effects have not yet been quantified because of the transition of diverse temporal and spatial scales including transformation processes. An aquatic ecosystem may be strongly influenced by agricultural emissions if surface flow directly occurs after the fungicide application which means on a short-term scale. Threatening danger for adjacent ecosystems might also result through leaching or erosion of cadmium accumulated in the soil.

Society sets preferences and priorities. Nowadays one of the most essential requirements emphasises that sustainability means precaution (Hofmeister, 1997). This demand should be integrated in deriving EEI and associated threshold ranges.

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SUMMARY

Agricultural production and its material and non-material emissions may cause side-effects in ecosystems. These effects have to be assessed and evaluated. Due to the high complexity of ecosystems and the diverse temporal and spatial scale transitions direct cause-effect relations cannot clearly be recognised. Therefore, an assessment is difficult.

The aim of the present study is to provide a tool that relates emissions of agricultural production and affected ecosystems. This tool represents an indicator approach. The needed indicators are defined as ecosystemic effect indicators (EEI). Subordinate objectives of the work are (1) to develop a plausible, transparent and comprehensible method to derive EEI and (2) to test the developed method for non-material and material inputs for affected agroecosystems in a case study. In combination with examinations done by colleagues at institutes of the University of Hohenheim and the University of Stuttgart the results of the present study aim to support efforts to enable and assess sustainable agriculture in the frame of an interdisciplinary project.

A literature review revealed that various indicators and indicator models are already available. Most environmental indicators can be assigned to the categories simple and systemic indicators. In spite of the variety of existing indicators those suitable for analysing ecosystems affected by emissions from agricultural production processes could not be identified. Further the application of current indicators is restricted to the spatial scales the indicator models were developed for, e.g., the national or global scale.

A multistage procedure is developed within this study which should be pursued in identifying indicators. To assess which emissions must be regarded in detail an estimation of relevance by means of an emission and input classification preceeds the indicator development. The classification follows a set of criteria. According to these criteria the emissions and the respective inputs are qualitatively and, as far as possible, quantitatively classified.

When deriving indicators either a top-down or a bottom-up approach is usually used. Top-down a main objective is stepwise broken down. Bottom-up each potential receptor for the impacts is compiled in detail. Following, the receptors are assigned and aggregated with regard to a main objective. It is shown In the present work that both approaches should be combined to overcome the shortcomings of each single one to deduce EEI. The derivation

of EEI is carried out by the following steps: 1) One starts top-down at the target "maintaining the ecosystem functioning", in this work depicted by the utility functions. A list with characteristics which are dependent on hierarchical levels is compiled for each relevant function. 2) Starting at one specific input a list of potential receptors is compiled bottom-up. These represent potential effect indicators. 3) By overlapping the lists of the steps 1 and 2 one yields EEI specific for the utility function and the input under consideration. The step 3 is performed by means of expert knowledge. The advantage of the indicator approach is its operativeness which is site-independent. In case of a concrete implementation different expressions of EEI are expected.

The application of the methodological approach for non-material and material emissions in a case study obtains distinct EEI with regard to the diverse inputs and utility functions considered. In some cases one joint aggregated EEI for various functions may be identified. For instance, the transformation function plays an essential role in nutrient cycling and hence represents an important prerequisite for the production function of an agroecosystem. One yields the following EEI for the transformation function: The respiratory intensity and the metabolic quotient ensue for the input of soil pressure, the biomass of earthworms ensue for the input of the fungicide carbendazim, the activity of the enzymes urease and amydase ensue for the input of nitrogen and the reproduction of earthworms and the biological activity of microorganisms ensue for the input of cadmium.

Temporal features are found to be of great importance for the presented indicator approach. The work demonstrates the importance of detecting consistencies between time frequencies of emerging stress factors and the varying sensitivity of receptors, e.g., during the seasons of a year.

In conclusion, the study demonstrates that the methodological approach connects undesired effects in ecosystems with causing emissions which result from agricultural land use. The results of the study show that EEI may be deemed to be promising tools to picture human influences in particular of agricultural production on ecosystems. The results of the case study provide the basis to assess effects on ecosystems for some major stressors. In cases where critical values are available site specific quantitative statements concerning ecological effects within the frame of sustainable agriculture are enabled by the present comprehensive method for the derivation of indicators. Subsequently, necessary measures can be deduced.

ZUSAMMENFASSUNG

Die landwirtschaftliche Produktion und ihre stofflichen und nicht-stofflichen Emissionen können umweltrelevante Nebeneffekte in Ökosystemen verursachen. Aufgrund der Komplexität von Ökosystemen und der verschiedenen zeitlichen und räumlichen Skalenübergänge ist die Kausalität von Ursache-Wirkungsbeziehungen jedoch oft nicht klar zu erkennen. Dadurch wird eine Bewertung erschwert.

Das Ziel der vorliegenden Arbeit ist die Bereitstellung eines Instrumentes, mit dem Emissionen aus der landwirtschaftlichen Produktion zu tangierten Ökosystemen in Beziehung gesetzt werden können. Dieses Instrument stellt ein Indikatoransatz dar. Die benötigten Indikatoren werden als ökosystemare Wirkungsindikatoren (ÖWI) bezeichnet. Folgende Teilziele ergeben sich für die Arbeit: (1) die Entwicklung einer klaren und nachvollziehbaren Methode zur Herleitung von ÖWI und (2) die Prüfung der entwickelten Methode in einer Fallstudie für nicht-stoffliche und stoffliche Einträge in tangierte Agrarökosysteme. Im Rahmen eines interdisziplinären Projektes, das an verschiedenen Instituten der Universitäten Hohenheim und Stuttgart durchgeführt wird, sollen die in dieser Arbeit gewonnenen Erkenntnisse dazu beitragen, eine nachhaltige Landwirtschaft zu ermöglichen und zu bewerten.

Eine Literaturanalyse zeigte, dass zahlreiche Umweltindikatoren und Indikatorenmodelle verfügbar sind. Die meisten Umweltindikatoren lassen sich den Kategorien einfache oder systemische Indikatoren zuordnen. Trotz der Vielfalt der verfügbaren Indikatoren war es jedoch nicht möglich, Indikatoren zu finden, die sich für eine Analyse von Ökosystemen eignen, die von landwirtschaftlichen Emissionen beeinflusst werden. Eine weitere Restriktion in der Anwendung ergibt sich dadurch, dass Indikatorenmodelle häufig für andere räumliche Skalen, z.B. für die nationale oder globale Skale, entwickelt wurden.

Im Rahmen dieser Untersuchung wurde ein mehrstufiges Vorgehen entwickelt, nach dem die Bildung von Indikatoren erfolgen sollte. Um einzuschätzen, welche der zahlreichen Emissionen genauer zu betrachten sind, wird in der vorliegenden Arbeit vorgeschlagen, der Indikatorenableitung eine Relevanzanalyse anhand einer Emissions- und Eintragsklassifizierung voranzustellen. Diese Klassifizierung enthält eine Reihe von Kriterien, nach

denen die Emissionen und späteren Einträge qualitativ und soweit möglich auch quantitativ eingeordnet werden.

Bei der Ableitung von Indikatoren wird aktuell üblicherweise entweder ein Top-down- oder ein Bottom-up-Ansatz angewendet. Top-down wird ein Hauptziel immer weiter in bestimmende Parameter aufgeschlüsselt. Bottom-up werden detailliert potenzielle Rezeptoren zusammengestellt und anschliessend einem Hauptziel zugeordnet. Diese Arbeit demonstriert, dass die beiden Ansätze bei der Ableitung der ÖWI kombiniert werden sollten. Die Indikatoren sollen - unabhängig auf welcher hierarchischen Ebene im Ökosystem sie gefunden werden - eine Verbindung zwischen Wirkung und Ursache verfolgen lassen. Die Ableitung von ÖWI erfolgt in folgenden Schritten: 1) Top-down wird vom Schutzgut "Erhaltung der Ökosystemfunktionen", hier der ”Utility“-Funktionen, ausgegangen. Für jede betrachtete Funktion wird eine Liste mit Charakteristika, die auf verschiedenen ökologischen Ebenen angesiedelt sind, erstellt. 2) Bottom-up wird vom Emittenten ausgehend für eine ausgewählte Emission bzw. den zugehörigen Eintrag eine Liste mit möglichen Rezeptoren erstellt. Diese repräsentieren potenzielle Wirkungsindikatoren. 3) Durch Überschneiden der Listen aus Schritt 1 und 2 erhält man den für die gewählte Funktion und den betrachteten Eintrag spezifischen ÖWI. Dieser Schritt erfolgt mit Hilfe von Expertenwissen. Ein großer Vorteil des methodischen Ansatzes ist seine standortunabhängige Funktionsfähigkeit. Bei der konkreten Anwendung ist eine je nach Standort unterschiedliche Ausprägung der ÖWI zu erwarten.

Die Anwendung der Methode in einer Fallstudie für nicht-stoffliche und stoffliche Einträge in ein Agrarökosystem erzielt je nach Eintrag und betrachteter Utility Funktion verschiedene ÖWI. In manchen Fällen kann ein gemeinsamer aggregierter ÖWI für verschiedene Funktionen identifiziert werden. Betrachtet man z.B. die Transformationsfunktion, die im Nährstoffkreislauf und damit auch als Voraussetzung für die Produktionsfunktion eines Agrarökosystems von Bedeutung ist, werden folgende ÖWI identifiziert: Für den Eintrag Bodendruck ergibt sich als ÖWI die Atmungsintensität und der metabolische Quotient, für das Fungizid Carbendazim die Regenwurmbiomasse, für Stickstoff die Urease- und Amydaseaktivität und für Cadmium die Regenwurmreproduktion und die biologische Aktivität von Mikroorganismen.

Der Faktor Zeit spielt im hier vorgestellten Indikatoransatz eine große Rolle. Es wird nachgewiesen, dass es für die Auswahl von ÖWI entscheidend ist, Übereinstimmungen zwischen der zeitlichen Frequenz einer Störung und der variierenden Empfindlichkeit des Rezeptors, z.B. im Jahresverlauf, zu identifizieren.

Mit dieser Arbeit wird gezeigt, dass ÖWI unerwünschte Wirkungen in Ökosystemen mit den sie verursachenden, aus der landwirtschaftlichen Produktion resultierenden, Emissionen verbinden. Die Methode zur Ableitung von ÖWI ist daher ein erfolgversprechendes Instrument, um menschliche Einflüsse, v.a. landwirtschaftlicher Produktionsprozesse, auf Ökosysteme abzubilden. Die Ergebnisse der Fallstudie bilden die Basis, um Wirkungen von potentiellen Stressoren für Ökosysteme zu bewerten. Für den Fall, dass kritische Werte für die ÖWI vorhanden sind, ist es möglich, standortspezifische quantitative Aussagen über ökologische Effekte der landwirtschaftlichen Produktion zu treffen. Anschließend können notwendige Maßnahmen abgeleitet werden, um die Nachhaltigkeit der Produktion zu unterstützen.

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X APPENDIX

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Table X1: Example of a classification for emissions of agricultural production and inputs in ecosystems (with a focus on production of Triticale). Primarily dominant sources of an emission are portrayed. In parenthesis shown are these of secondary importance

Category		**Emission**														
		Soil pressure *	Cadmium*	PO^{4-}	NO^{3-}	NO_x	NH_3	N_2O	CO_2	SO_2	IPU	Fluroxy	Carbend *	Flusilaz	CCC	Etheph
Source	Preprocessing chains (covers e.g. fertiliser production)		X			X	X	X	X	X						
	Production (covers production and utilisation of Triticale)	X[a]	X[c]	X[c]	X[c]	X[a, b, d]	X[c]	X[b, d]	X[a, b]	X	X	X	(X)	X	X	X
	Product application (on the field)	X	X[c]	X[c]	X	X	X	X	X[a]		X	X	X	X	X	X
Spatial kind of source	Point					X[d]		X[d]		X[d]	(X)[e]	(X)[e]	(X)[e]	(X)[e]	(X)[e]	(X)[e]
	Band	X				X[a]							(X)			
	Area		X	X	X	X[a, b]	X	X[b]	X		X	X	X	X	X	X
Temporal aspects of emission	Unique #										(X)[e]	(X)[e]	(X)[e]	(X)[e]	(X)[e]	(X)[e]
	Periodical	X (~ 17 times/a)	X (P-fertilisation)	X Sep tem ber	X	X	X	X	(X)		X	X	X June	X	X	X
	Continuos		X			X[d]		X[d]	X	X						
Properties of emissions	Volatile					X	X	X			low	medium	medium	extremly high		low
	Water soluble				X				X		medium	medium	low	medium-low	high	extremly high
	Mobile				X		X									
	Persistent	X	X					X			low[f]	low[f]	medium[f]	nt	low[f]	very low[f]
	Toxic		X			X	(X)			X			X			

Category		Emission														
		Soil pressure*	Cadmium*	PO^{4-}	NO^{3-}	NO_x	NH_3	N_2O	CO_2	SO_2	IPU	Fluroxy	Carbend*	Flusilaz	CCC	Etheph
Exposition Transport process	**Water/soil**	X	X	X	X		X		X		X	X	X	X	X	X
	Solution		X	X	X		X		X		X (SF)		X			X (SF)
	Particle bounded		X	X									X			
	Air		X			X	X	X	X	X	(X)	X	X	(X)	X	X
	Gaseous					X	X	X	X	X	X		X	X		
	Particle bounded		X			X	X									
Radius of effect	Local	X	X	X	X	X	X				X	X	X		X	X
	Regional	X	X	X	X	X	X			X	X		X			X
	Global				(X)			X	X	X						
Time scale of effect	Short-term	X	(X)	X	X	X	X		X		X	X	X	X	X	X
	Middle-term		X	X	X	X	X	X	X	X		(X)	(X)			
	Long-term	X	X	X		X	X	X	X	X						
Site of effect	Terrestrial ecosystem	X	X		X	X	X	(X)	(X)		(X)	X	X	X	(X)	X
	Aquatic ecosystem	(X by erosion)	X	X	X	X	X	(X)	(X)	X	(X)		X RP	X		X RP

*: Exact effect cf. to lists of receptors and effects (X13 - X20)
\# Dependent on duration of observance

a Use of machinery
b Soils (biotic)
c Inorganic fertiliser (chem.-phys.)
d Heating plant (technique)
e Point emission occurring at filling or cleaning of plant protection equipment
f Very low = DT50 < 20 d, low = DT50 < 50 d, middle = DT50 < 365 d, high = DT50 > 365 d

nt Not traceable
SF Surface flow
RP Mentioned in the regulation for prevention of water

Table X2: Cadmium contents of phosphate and inorganic nitrogen fertilisers (Biomasse, 1998; Wilcke and Döhler, 1995)

Fertiliser	Cadmium in mg · kg^{-1}
P Fertiliser	
Triple superphosphate	25 – 30,6
Thomas phosphate	0,1 - < 2
Superphosphate	1,4 – 21
Hyperphosphate	16,1
Alkalisintersphosphate	0,84
Rhenania phosphate rock	< 2
Partly digested phosphate rock	7,2
Soft phosphate rock	11,4
N Fertiliser	
Calcium ammonium nitrate	0,24 – 0,38
Ammonium urea solution	0,003
Urea	< 0,1 – 0,2
Ammonium sulphate	< 0,1
Calcium nitrate	0,1
Multinutrient Fertiliser	
NP Fertiliser	7 – 15
PK Fertiliser	2 – 3,6
NPK Fertiliser	0,2 – 4,9

Table X3: Level-dependent abiotic characteristics of the buffer function

FUNCTION	Abiotic characteristics of Level II	Level I *	Level 0 *
BUFFER FUNCTION[+]	Soil structure[#]	Infiltration Percolation Preferential flow Evaporation	Distribution and amount of ▪ fissures ▪ cracks ▪ cavities ▪ burrows ▪ root channels ▪ macropores Frequency of macropores Pore continuity Kind of structure Water content Kind of texture Useful field capacity Particle size and surface Total surface of active particles Field capacity Aggregate stability Peds ▪ size ▪ shape
	Soil texture	Mineral weathering	Amount of ▪ clay ▪ loam ▪ silt ▪ sand Clay minerals Formation of secondary silicates Carbonates Hydrogen carbonates Calcium saturation Sulphates Silicates Particle surface ▪ charge ▪ valence ▪ kind of charge (permanent/variable) Functional groups Humus content Kind of humus Degree of humification Content and distribution of ▪ humin substances ▪ iron oxides ▪ aluminium oxides ▪ silicium oxides ▪ hydroxides ▪ fine clay

FUNCTION	Abiotic characteristics of Level II	Level I *	Level 0 *
BUFFER FUNCTION+		Ion exchange Exchange capacity	Anion exchange capacity Cation exchange capacity Ion fixation Coagulation Attractive forces Hydrolysis reactions Hydratation Protolysis Complexation Chelation Precipitation Adsorption ▪ specific ▪ unspecific Base saturation
		Acidification Redox conditions	Soil pH Acid neutralisation capacity Proton concentration Acidity Electrical conductivity Sulfurication Oxidation of iron sulphides

+ Further external factors effect the buffer function:
- Precipitation: distribution, kind and rate
- Insolation: temperature

* A clear separation of characteristics is often not possible. Partly the characteristics of level I (subsystems) or 0 (elements, single processes) might be also assigned to other characteristics of the respective higher level. Nevertheless they are only once mentioned in the table, namely where they have been thought to be strongly important

Soil structure is in so far important as it determines the transport pathway of the substances

Table X4: Level-dependent biotic characteristics of the buffer function

FUNCTION	Biotic characteristics of		
	Level II	**Level I**	**Level 0**
BUFFER FUNCTION		Decomposition	Microbial activity Enzymatic activity Assimilation Content of carbon dioxide Break-down of fresh litter by soil biota Mineralisation Fixation Humus form Degree of humification Burrowing animals Shreddering of organic substance

Table X5: Level-dependent abiotic characteristics of the filter function

FUNCTION	**Abiotic characteristics of**		
	Level II	**Level I ***	**Level 0 ***
FILTER FUNCTION[+]	Soil structure	Structuring Porosity Preferential flow Evaporation Infiltration Percolation Peloturbation	Shrinking and cracking of clay Pore volume Pore size distribution ▪ macropores ▪ fissures ▪ burrows ▪ lenses ▪ root channels Order of soil particles Particle size Aggregates ▪ internal organisation ▪ stability ▪ size distribution Pore permeability Pore continuity Infiltration capacity Rate of percolation Hydraulic conductivity Field capacity Water-filled porosity Diffusion Convection
	Soil texture	Mineral weathering	Amount of ▪ clay ▪ silt ▪ sand ▪ loam Clay-humus complexes Fine clay fraction Calcium-saturation Ion valence Ion radius Ion concentration Ion content ▪ anions ▪ cations Metal oxide content Hydrophilic groups Repulsive forces Attractive forces Dispersion Peptisation Flocculation Suffusion

+ Further external factors effect the filter function:
- Precipitation: distribution, kind and rate
- Insolation: temperature
- Groundwater influence
- Surface runoff, interflow

* A clear separation of characteristics is often not possible. Partly the characteristics of level I (subsystems) or 0 (elements, single processes) might be also assigned to other characteristics of the respective higher level. Nevertheless they are only once mentioned in the table, namely where they have been thought to be strongly important

Table X6: Level-dependent abiotic characteristics of the habitat function

FUNCTION	Abiotic characteristics of Level II	Level I *	Level 0 *
HABITAT FUNCTION[+]	Soil texture		Distribution of ▪ clay ▪ loam ▪ silt ▪ sand Particle size Particle size distribution Stone content Humus content
	Soil structure	Porosity Structuring	Distribution, size and kind of pores ▪ fissures ▪ cracks ▪ channels ▪ macropores Pore volume Pore continuity Pore permeability Penetration resistance Bulk density Aggregate stability Mechanical barriers Surface seals, crusts Hard-, claypans
	Soil air	Porosity Structuring Aeration	Air-filled porosity Air capacity Oxygen content Carbon dioxide content Methane content Diffusion Convection
	Soil water	Infiltration Percolation Preferential flow Evapotranspiration	Water-filled porosity Water content Useful water Water retention Pore size distribution Pore continuity Hydraulic conductivity
	Energy balance		Heat capacity Heat conductivity Soil colour Soil temperature Soil respiration
		Photosynthesis	Flux of energy/carbon to higher levels

FUNCTION	Abiotic characteristics of		
	Level II	**Level I ***	**Level 0 ***
HABITAT FUNCTION+	Nutrient cycling	Ion exchange Ion transport	Ion ▪ availability ▪ fixation ▪ exchange capacity Ion content ▪ anions ▪ cations Nutrient content Mineralisation Immobilisation
		Milieu Redox conditions	Soil acidity Soil pH Electrical conductivity Oxygen content Methane content Redox potential
	Pollutant cycling		Pollutant content Kind of pollutant Mobility Toxicity Persistence

+ Further external factors effect the habitat function
- Precipitation: distribution, kind and amount
- Water table
- Insolation: temperature

* A clear separation of characteristics is often not possible. Partly the characteristics of level I (subsystems) or 0 (elements, single processes) might be also assigned to other characteristics of the respective higher level. Nevertheless they are only once mentioned in the table, namely where they have been thought to be strongly important

Table X7: Level-dependent biotic characteristics of the habitat function: concerning flora (fungi, plants, crops) and fauna (micro-, meso-, macro-fauna)

FUNCTION	**Biotic characteristics of**		
	Level II	**Level I ***	**Level 0 ***
HABITAT FUNCTION	Biodiversity Biomass production Nutrient cycling	Species ▪ diversity ▪ distribution ▪ abundance Population dynamic	Weeds Migration ▪ larks ▪ rabbits ▪ moles ▪ mice ▪ rodents
		Rate, abundance and distribution of ▪ Producers ▪ Decomposers ▪ Consumers ▪ Reducers	Earthworms Snails Enchytraeids Isopods Diptera Ants Beetles Spiders Bees Butterflies Moths Collembola Protozoa Nematodes Mites Bacteria Algae Kind and amount of enzymes
		Rhizosphere	Fungi Mycorrhizal-fungi Rhizobium bacteria Root exudates
		Food net/ -chain	Predator-prey-ratio
		Assimilation Decomposition	Microorganism activity Enzymatic acitivity (e.g. CMCase)

*A clear separation of characteristics is often not possible. Partly the characteristics of level I (subsystems) or 0 (elements, single processes) might be also assigned to other characteristics of the respective higher level. Nevertheless they are only once mentioned in the table, namely where they have been thought to be strongly important

Table X8: Level-dependent abiotic characteristics of the production function

FUNCTION	Abiotic characteristics of		
	Level II	**Level I ***	**Level 0 ***
PRODUCTION FUNCTION+	Soil texture		Distribution and content of ▪ clay ▪ loess ▪ sand ▪ loam Humus ▪ content ▪ form Adsorption ▪ specific ▪ non-specific
	Soil structure	Peloturbation Structuring	Pore size ▪ fissures ▪ cracks ▪ channels Pore volume Pore distribution Aggregate shape Interparticle forces Bulk density Penetration resistance Accessibility for roots
	Soil water	Infiltration Percolation Evaporation	Field capacity Useful field capacity Non-useful water Water retention capacity Water table
	Soil air	Porosity Aeration	Content of ▪ oxygen ▪ methane Pore size Pore volume Air-filled pores Pore distribution Niches for organisms
	Energy balance	Heat flux Porosity	Soil colour Humus content Heat capacity Transpiration Respiration intensity Metabolic quotient

FUNCTION	Abiotic characteristics of Level II	 Level I *	 Level 0 *
PRODUCTION FUNCTION+	Nutrient cycling	Nutrient turnover Nutrient pool Ion exchange	Nutrient ▪ content ▪ availability ▪ delivery Ion content Cation exchange capacity Anion exchange capacity Clay content Humus ▪ content ▪ composition Availability of trace elements Pollutants ▪ content ▪ availability ▪ toxicity
		Milieu Redox conditions	Soil pH Redoximorphy Sesquioxides Electrical conductivity

+Further external factors effect the production function:

- Fertiliser application, kind, distribution
- Pesticide application, time moment, frequency of use, concentration, kind
- Mechanical treatment
- Irrigation
- Precipitation: distribution, kind and amount
- Insolation: temperature, transpiration

* A clear separation of characteristics is often not possible. Partly the characteristics of level I (subsystems) or 0 (elements, single processes) might be also assigned to other characteristics of the respective higher level. Nevertheless they are only once mentioned in the table, namely where they have been thought to be strongly important

Table X9: Level-dependent biotic characteristics of the production function

FUNCTION	Biotic characteristics of		
	Level II	**Level I ***	**Level 0 ***
PRODUCTION FUNCTION	Nutrient cycling Biomass production	Rate, abundance and distribution of plant and weed populations Rate, abundance and distribution of ▪ producers ▪ decomposers ▪ consumers - phytophages - zoophages ▪ reducers Photosynthesis Bioturbation	Floral species and their individuals Faunal species and their individuals Enzymatic activity Microbial activity Species diversity of ▪ earthworms ▪ microorganisms ▪ fungi ▪ algae ▪ mycorrhizae Content of burrowing animals Transpiration Ammonification Ammonifying bacteria Nitrification Nitrifying bacteria
	Biocoenosis	Food web Food chain Species ▪ distribution ▪ number ▪ kind	Predator-prey-ratio Individuals of ▪ producers ▪ consumers ▪ decomposers ▪ reproducers Number of individuals Rate of reproduction

* A clear separation of characteristics is often not possible. Partly the characteristics of level I (subsystems) or 0 (elements, single processes) might be also assigned to other characteristics of the respective higher level. Nevertheless they are only once mentioned in the table, namely where they have been thought to be strongly important

Table X10: Level-dependent abiotic characteristics of the transformation function

FUNCTION	Abiotic characteristics of		
	Level II	**Level I ***	**Level 0 ***
TRANSFORMATION FUNCTION +	Soil structure	Porosity	Pore size Pore volume Pore size distribution Pore frequency
	Soil air	Aeration	Oxygen content Carbon dioxide content
	Soil water		Water content Useful water Percolation rate
	Nutrient cycling	Nutrient ▪ mobilisation ▪ immobilisation Nutrient ▪ sorption ▪ desorption ▪ resorption Humus decomposition Humus transformation	Mineral transformation Fermentation Ammonification Mineralisation Sulfurication Ion binding Nitrate reduction Hydrolysis Proton ▪ production ▪ consumption Humin acids Humin substances Litter ▪ break down ▪ mineralisation
		Photochemical processes	
		Milieu Redox conditions	Soil pH Electrical conductivity Hydrolysis (Catalase) Oxidation Reduction
	Heat flux	Porosity	Soil temperature Soil colour Humus content Heat ▪ capacity ▪ conductivity
	Energy balance	Photosynthesis	Flux of energy and carbon Uptake of carbon dioxide Assimilation Respiration intensity Metabolic quotient

+ Further external factors effect the transformation function:
- Water table and groundwater influence
- Insolation: temperature
- Moisture

* A clear separation of characteristics is often not possible. Partly the characteristics of level I (subsystems) or 0 (elements, single processes) might be also assigned to other characteristics of the respective higher level. Nevertheless they are only once mentioned in the table, namely where they have been thought to be most appropriate

Table X11: Level-dependent biotic characteristics of the transformation function which depends strongly on the habitat function

FUNCTION	Biotic characteristics of Level II	Level I	Level 0
TRANSFORMATION FUNCTION		Decomposers Bioturbation	Number and kind of ▪ Enchytraeids ▪ Earthworms ▪ Snails ▪ Isopods ▪ Ants ▪ Arthopods ▪ Diptera ▪ Rhizobium ▪ Actinomycetes ▪ Rodents Fermentation Break down of organic matter Decay Humus degradation Humification
		Consumers	Phytophages ▪ bacteria ▪ fungi ▪ algae Zoophages ▪ collembola ▪ protozoa ▪ nematodes ▪ mites
		Reducers Microbial community: ▪ Density ▪ Composition	Kind/ density of microorganisms, above all bacteria Denitrification Nitrification ▪ Nitrobacter ▪ Nitrosamonas Azotobacter Metabolisation Enzymes ▪ species ▪ activity ▪ concentration - glucoscidase - thiosulphate - S-Transferase - asparginase - glutaminase - amidase - proteinase - peptidase - phosphatase - sulphatase - urease
		Rhizosphere	Fungi Mycorrhizal bacteria Rhizobial bacteria Root exudates
		Photosynthesis	Assimilation Production rate of carbon dioxide

Table X12: Level-dependent characteristics of the storage function with regard to water and nutrient storage

FUNCTION	Abiotic characteristics of		
	Level II	**Level I ***	**Level 0 ***
STORAGE FUNCTION+	Soil structure	Porosity Peloturbation	Pore volume Pore size Pore distribution Pore size distribution Content of ▪ fissures ▪ macropores Order of soil particles Interparticle forces Kind of binding Adhesion Cohesion Aggregates ▪ stability ▪ size distribution Particle aggregation Bulk density
	Soil texture	Ion exchange	Amount of ▪ clay ▪ sand ▪ loam ▪ silt ▪ fine earth Ratio of fine earth/coarse earth Stone content Fine clay fraction Cation exchange capacity Anion exchange capacity Kind of attractive forces Ion charge Free exchange sites Content and kind of ▪ humus ▪ humic substances
	Soil water	Water cycling	Pore permeability Pore continuity Infiltration capacity Hydraulic conductivity Rate of percolation Field capacity Water table
	Soil biota	Bioturbation	Creation of pores Creation of aggregates Root activity

+ Further external factors effect the storage function:
- Precipitation: distribution, kind and rate
- Insolation: temperature, evaporation
- Groundwater influence
- Surface runoff, interflow, preferential flow

*A clear separation of characteristics is often not possible. Partly the characteristics of level I (subsystems) or II (elements, single processes) might be also assigned to other characteristics of the respective higher level. Nevertheless they are only once mentioned in the table, namely where they have been thought to be strongly important

Table X13: List of abiotic receptors and effects with regard to the input soil pressure. Analysed was the literature which can be taken from the references of section X

SOIL PRESSURE	Receptors and Effects* Abiotic			Environmental consequences
	Level 0	Level I	Level II	
	Pore size distribution Pore volume⇓ Macropores⇓ ➘ Air capacity⇓ Micropores⇑ ⇒ useful water⇓	Porosity⇓	Soil structure+	Seed rise retarded
	Soil density ▪ in the short run⇓ ▪ with increasing compression⇑			Compaction ⇑ Structural change under the plough zone ⇒ plough sole ⇒ root barrier ⇒ long-term persistent compaction ⇒ Yield ⇓
	Change of the macrostructure Change in ▪ aggregation ▪ aggregate stability			Accessibility for roots⇓
	Soil substance in a three-dimensional compartiment⇑ Contact area between soil particles ⇑			⇒Runoff and soil erosion⇑
	➘ Shear resistance⇑ Shear strength ⇑ linear with number of overrunning ➘ load capacity⇑ (in the short run, in renewed loading: load capacity⇓) Soil resistance⇑ (⇒ cost of energy ⇑) Partly formation of a plough layer			Erosion ⇒ loss of nutrients ⇒ inhibited biomass production
	Cohesion Penetration resistance⇑ Earthworm channels⇓			Less surface area ⇒ chemical processes influenced

SOIL PRESSURE	Receptors and Effects* Abiotic Level 0	Level I	Level II	Environmental consequences
	Pore size ▪ macopores⇓ ▪ micropores⇑ Pore size distribution Soil aeration Soil air capacity ⇓ Aerated pore volume ⇓ Air permeability ⇓ Diffusion ⇓ Oxygen deficiency ⇑ Partly reductive conditions	Porosity	Soil air	Silting up Erosion⇑ Wind erosion ⇑ (a short period after harvest) Soil volume⇓ Nutrient loss ▪ Eutrophication ▪ Pollutant accumulation Surface sealing High compaction ⇒ Gas transport⇓⇓ ⇒ Denitrification⇑ ⇒ Unproductive nitrogen-loss⇑ ⇒ Oxygen deficiency ➘ reduced nitrogen uptake Soil decompaction via fauna ⇓ Biological transformations ⇓ ➘ Microbial activity ⇓ Silting up of surface soil High water content
	Water retention ⇓ Infiltration ⇓ Run-off ⇑ Evapotranspiration⇓ Hydraulic conductivity ⇓ Saturated conductivity ⇓ Water transport ⇓ (soil moisture influenced up to 2m depth) Degree of water saturation ⇑		Soil water	Chemical and biological processes influenced ▪ Plant growth ⇓ ▪ Groundwater formation ⇓ Surface runoff ⇑ Danger of erosion ⇑ Later warming up of the soil surface Differences in temperature ⇓
	Heat capacity ⇓ Heat efficiency ⇓ Potential of warming up ⇓ Heat conduction ⇓		Soil temperature	Soils less able to warm up Influence on chemical and biological processes Plant growth ⇓ Nutrient cycling slower Activity of organisms⇓
	Humus decomposition Nitrogen availability ⇓	Nutrient mobilisation ⇓ Nutrient transport ⇓	Nutrient cycling	

*: Soil pressure effects may be influenced by moisture
+:Main destruction in the first year
⇑ increases
⇓ decreases

Table X14: List of biotic receptors and effects with regard to the input soil tillage. Analysed was the literature which can be taken from the references of section X

SOIL TILLAGE	**Receptors and effects** **Biotic** **Level 0**	**Level I**	**Level II**
	Disturbance of the soil fauna (breeding) (mechanical herb control) Promotion of less competitive species Biomass ⇓ Death of animals (Harvest) destruction of ecological valuable plant species before the ripening of the seeds (stubble treatment)	Food chain /web	Biodiversity Change of habitat
	Oppression of the herbicides Death/violation of organisms of different states of development Transfer (bury) of soil organisms, seeds, plants	Producer Shift in species composition Vegetation ▪ composition ▪ society	Biodiversity Phytocoenosis Biocoenosis Nutrient cycling Biomass production
	Earthworms Enchytraeids Snails Isopods Ants Diptera Transfer and burrowing of soil organisms Soil organisms ⇓ Soil macrofauna individuals ⇓ Soil mesofauna individuals⇓ Number of earthworms ⇓ (directly killed or injured) Especially smaller species of the upper soil influenced Movement of soil fauna ⇓ Nutrient decomposition ⇓ Nutrient transformation ⇓	Decomposer species Population ⇓ Bioturbation ⇓	
	Oxygen content Enchytraeids⇓ Collemboles⇓ Mites⇓	Consumer species	

SOIL TILLAGE	Receptors and effects Biotic Level 0	Level I	Level II
	Phytophages ▪ bacteria ▪ fungi ▪ algae Zoophages ▪ collembola ▪ protozoa ▪ nematodes ▪ mites Transfer (bury) of soil organisms Death and violation of ▪ soil organisms ▪ birds ▪ small mammals at different states of development ▪ reptiles	Consumer	Nutrient cycling Biomass production Change of the ▪ phytocoenosis ▪ biocoenosis
	Bacteria Fungi Algae Enzymes Microorganisms ⇑ ▪ better distribution of the organic nutrients ⇒ Mineralisation ⇑	Reducer	

⇑increases
⇓decreases

Table X15: List of abiotic receptors and effects with regard to the input carbendazim. Analysed was the literature which can be taken from the references of section X

CARBENDAZIM	**Receptors and effects*** **Abiotic**		
	Level 0	**Level I**	**Level II**
	Phosphorus availability⇑ (at low Carbendazim doses)	Phosphorus cycling	
	Aggregates Macropores		Soil air
		Preferential flow Infiltration rate	Soil water
	Aggregate stability		Soil structure

* Carbendazim effects may be influenced by pH values and the clay content
⇑ increases
⇓ decreases

Table X16: List of biotic receptors and effects with regard to the input carbendazim. Analysed was the literature which can be taken from the references of section X

CARBENDAZIM	**Receptors and effects*** **Biotic** **Level 0**	**Level I**	**Level II**
	Ammonification NH4-N ⇑ Nitrification NO3-N ⇓ Litter decomposition⇓	Nitrogen cycling	Nutrient cycling
	Bacteria ▪ ammonifying⇑ (at low dose) ▪ nitrifying - Nitrosomas ⇓ - Nitrobacter ⇓		
	Lumbricus terrestris ▪ feeding activity ⇓ ▪ dry weight of earthworm excrements⇓ Enchytraeids ⇓ CMCase-Activity ⇓ Break down of litter ⇓	Decomposers ⇓	
	Lumbricus terrestris⇓	Earthworm population ⇓	Biomass production Biocoenosis
	Eisenia andrei: reproduction ⇓ ▪ cocoon production⇓ ▪ fertile cocoons⇓ ▪ number of juveniles⇓	Decomposers Decomposition⇓	Faunal biomass ⇓
	Eisenia fetida: cocoon production ⇓		
	Eisenia caliginosa: Reproduction ⇓ as a function of ▪ juveniles ▪ adults ▪ organic carbon content ▪ kind of minerals		
	Enchytraeids: Reproduction ⇓		
	Growth conditions of ▪ Microorganisms ▪ Microflora	Population⇓	

Carbendazim effects may be influenced by pH values and the clay content
⇑ increases
⇓ decreases

Table X17: List of abiotic receptors and effects and environmental consequences with regard to the input cadmium. Analysed was the literature which can be taken from the references of section X

CADMIUM	**Receptors and Effects*** **Abiotic** **Level 0**	**Level I**	**Level II**	**Environmental consequences**
	Occupation of ion exchange sites Adsorption on exchangers, e.g. humus and sesquioxides at pH >6 (not in acid soils), less on clay $Cd(OH)_2$ $Cd(OH)^-$ $CdCO_3$ (at pH>7)	Cation exchange capacity Availability for plants	Nutrient cycling/ pollutant cycling	Cadmium – accumulation in the upper soil horizons (0-30cm)
	Formation of stable chloride complexes with Cd			Diffusion of Cd-Chloro-complexes towards the root surfaces, direct transpassing trough the plasma membranes, plant availability⇑
	Formation of Cd-hydroxo-complexes			
	Diffusion into oxide particles Strong adsorption on iron oxides			Heavy metal availability ⇓
	Accumulation of soil Cadmium during the period of fertilisation with phosphorus	Cadmium-supply⇑ Plant availability		Accumulation of Cadmium in the soil, in the plants
	Leaching or free availability of Cd^{2+} in acid soil pH values (pH<5.5)			Leaching of Cadmium into the groundwater Accumulation of Cadmium in the food chain via Cd^{2+} - accumulation by plants and consumers

Cadmium effects may be influenced by pH values, the humus and clay content
⇑ increases
⇓ decreases

Table X18: List of biotic receptors and effects with regard to the input cadmium. Analysed was the literature which can be taken from the references of section X

CADMIUM	Receptors and effects Biotic Level 0	Level I	Level II
	Accumulation in the flora individuals (in leaf tissue and roots more than in blooms, fruits and seeds) Uptake of Cadmium in grain seeds⇑ Accumulation of Cadmium in ▪ tobacco leaves ▪ sun flower seeds (0.79-1.17mg Cd · kg^{-1}) ▪ carrots Cadmium uptake highly correlated with NH_4NO_3 – Cd-concentration and exchangeable Cd Stigma sensitive reacting on low Cd-concentrations Pollen growth⇓	Cycling of trace elements	Nutrient cycling
	Earthworms Reproducton ⇓ Growth ⇓ *Eisenia andrei*: ▪ descendants/worm ⇓ ▪ cocoon production ⇓	Decomposition	
	Influx: soil-plant: high, uptake of 1-5% of the cadmium soluted Distribution factor of root:shoot for Cadmium on average: 4 Translocation factor: shoot:seed for Cadmium on average: 0,27	Trace element leaching	
	Soil microorganisms: ▪ Metabolic capacity⇓ ▪ Respiration rate⇓ ▪ CO_2 ⇓ Activity of ▪ Cellulase⇓ ▪ Phosphatase⇓ ▪ Amylase⇓ ▪ Nitrogenase⇓ High nitrogen accumulation ⇒ nitrifying bacteria affected Nitrifying bacteria more tolerant than microflora Immobilisation of mineral nitrogen⇓	Nutrient turnover	

CADMIUM	Receptors and effects Biotic Level 0	Level I	Level II
	Biological activity ⇓ (e.g.mineralisation, air nitrogen fixation) Nodule formation of beans⇓		
	Resistance at high Cadmium concentration: ▪ bacteria⇑ ▪ actinomycetes⇓	Change in distribution of species spectrum	Biodiversity
	Lumbricus: accumulation factor: 11-22 Bioaccumulation ⇑ Cadmium in earthworms⇑ (with inorganic fertilisation stronger than with organic fertilisation)	Earthworm population Accumulation in the food chain ⇒ biocycling of Cadmium	
	Cadmium content of earthworm tissue⇑ Cadmium concentration in *Dendrobaena veneta* ⇑	Bioavailability	
	Eisenia fetida: ▪ growth⇓ ▪ cocoon production⇓		
	Content in producer individuals ⇑ (e.g. in spinach shoot) Content in consumer individuals⇑ (flora) Accumulation in herbivores higher than in carnivores Accumulation factor Herbivores/Producers ca. 15µg · g^{-1} (dry weight)	Food chain	Food web
	Degradation of Thylakoid membrane ⇒ Photosynthesis II-activity inhibited Effect on Calvin-cycle ▪ Excess of ATP and NADPH ▪ Photosynthesis II-activity inhibited	Photosynthesis ⇓	Biomass production Plant growth⇓
	Interactions with Zinc: Zinc addition: uptake of Cd in wheat grains up to 50% ⇓: Decay of the membrane uptake of cadmium in tomatoes⇓ at the state of zinc-deficiency: mobilisation of cadmium with the excretion of phytosiderophores	Plant physiology	
	Root growth ⇓	Plant nutrition⇓	
	Bioavailability ⇑ if pH value ⇓	Agricultural plant and crop species and populations	Yield ⇓ depending on plant species and soil properties

⇑ increases
⇓ decreases

Table X19: List of abiotic receptors and effects with regard to the input inorganic Nitrogen. Analysed was the literature which can be taken from the references of section X

NITROGEN	Receptors and Effects Abiotic			Environmental consequences
	Level 0	**Level I**	**Level II**	
	NO_3^-, NH_4^+; N_{min}	Nitrogen pool ⇑	Nitrogen cycling	Plant nutrition deficiencies of ▪ N ▪ Mg ▪ K ▪ Ca Resistance problems
	Nitrogen-bindings Ammonia, NH_4^+ NO_3^- N_{anorg} (NH_4^+, ammonia, NO_3^-, NO_2^-) Nitrogen-immobilisation NH_4^+ Nitrogen-fixation Humic substances Clay minerals Clay-humus-complexes Iron-oxides or hydroxides Aluminium-oxides or hydroxides Denitrification NH_4^+ Ammonium-fixation			Nitrogen ▪ adsorbed ▪ plant available Soil acidification Leaching into the groundwater NH_4^+ -fixation in interlayers of clay minerals In groundwater- or stagnant water-influenced soils loss of nitrogen in agricultural systems
	NO_3^-, NH_4^+ Humus content Clay coatings Iron-oxides or hydroxides Aluminium-oxides or hydroxides Pore distribution	Adsorption capacity Buffer capacity Porosity	Soil structure	Leaching of NO_3^- with the percolation water, because of weak bindings with soil colloids negatively charged
	Gas diffusion coefficient	Ammonia volatility (up to 70%)	Soil air	Loss of nitrogen Greenhouse gas
	Gas diffusion coefficient	N_2O-formation		
	Aerobic and anaerobic protein decomposing	Exothermal processes	Heat flux	
	NO_3^- (NH_4^+)	Nitrogen leaching	Soil water	Nitrogen removal from the root zone, consequently plant availability reduced

NITROGEN	Receptors and Effects Abiotic Level 0	Level I	Level II	Environmental consequences
	Ammonia, NH_4^+	Soil acidification		Acidification potential of nitrogen ⇑ Plant available Mg, Ca, K ⇓ Release of ecotoxical Al^{3+}, Fe^{3+} Reduction of cation exchange capacity Nutrition deficiencies

⇑ increases
⇓ decreases

Table X20: List of biotic receptors and effects with regard to the input inorganic Nitrogen. Analysed was the literature which can be taken from the references of section X

NITROGEN	Receptors and Effects Biotic Level 0	Level I	Level II
	Activity of urease ⇓ Activity of amydase ⇓		Nitrogen cycling
	Nitrosomonas Nitrobacter Nitrification ⇑	Nitrogen pool	
	Achromobacter Pseudomonas Denitrification		
	Ammonia formation Ammonification ⇑		
	Nitrogen fixing microorganisms with nitrogenase Nitrogen-fixation ⇓ VA-mycorrhiza of agricultural plants		
	Lumbricus terrestris (optimum 12-24)	C/N ratio	
	pH value ⇓, influence on: ▪ Earthworms ▪ Nematodes ▪ Collembola ▪ Mites	Change of species Change in population size Change in population	Soil structure Nutrient cycling
	Number of individuals: *Lumbricus terrestris* ⇓		
	pH value⇑ ⇒ activity of microorganisms⇑	Qualitative change of species spectrum	
	Soil organisms	Kind of species	Biodiversity
	Appearance of *Urtica, Sambucus*	Shift in species spectrum	
	Fungi Bacteria Higher plants	Shift in kind and number of species	Biocoenosis
		Competition between agricultural plants and natural vegetation	

NITROGEN	Receptors and Effects Biotic		
	Level 0	**Level I**	**Level II**
	N $_{anorg}$⇑ ⇒ Root growth ⇑ - depth - area of growth drought/dryness resistance⇑ (e.g. grass) Root exudates⇑ Bacteria⇑ Fungi⇑ Actinomycetes⇑ (with regard to NPK-fertiliser) Heterotrophic microorganisms	Biomass activity⇑	(Plant) biomass production⇑
	Proteins⇑ Competition⇑	Plant contents	
	in a surplus: weakening of the plant fibres, saccharides⇓		
	Later blooming Later ripeness Less resistance towards illness and pests	Growth Plant Health	

⇑ increases
⇓ decreases

Table X21: Ecosystemic effect indicators for an agroecosystem regarding the utility functions habitat, transformation, filter, buffer, production and storage and the inputs soil pressure, carbendazim, inorganic nitrogen and cadmium

Function	**Soil pressure**	**Carbendazim**	**Inorganic nitrogen***	**Cadmium**
Habitat	Macro porosity	Number of juvenile earthworms or reproduction rate of earthworms or cocoon production of earthworms	Shift in species of weeds Shift in species spectrum of soil organisms	Ratio of actinomycetes/bacteria Cocoon production of earthworms Respiration of microorganisms
Transformation	Respiration intensity and metabolic quotient	Biomass of earthworms and enchytraeids	Urease activity Amydase activity	Biomass of earthworms (especially of *Dendrobaena veneta, Lumbricus terrestris*)
Filter	Pore spectrum, especially pore volume between 1 and 100 µm	Number and distribution of macropores	-	-
Buffer	-	Humus composition	N-min content	With Cd occupied ion exchange sites
Production	Penetration resistance or macro porosity	Biomass of earthworms and enchytraeids	Urease activity Amydase activity	Biological activity of microorganisms (activity of cellulase, phosphatase, amylase, nitrogenase in microorganisms) Reproduction rate of earthworms
Storage	Field capacity[+]	Humus composition[#]	-	With Cadmium occupied ion exchange sites

*: For nitrogen it is difficult to identify EEI because nitrogen exerts minor negative effects on the function characteristics
-: No direct ecosystemic effect indicator identified with regard to this input and utility function
+: Regarding water storage
#: Regarding nutrient storage

Table X22: Examples of threshold values as available in literature exemplary shown for the material input Carbendazim faced to the EEI proposed

Ecosystemic effect indicator	Threshold ranges	Reference
Number of juvenile earthworms	LC_{50}: (*Lumbricus terrestris*): 2.6 mg kg^{-1};	(van Gestel *et al*., 1992), (van Gestel, 1992)
	LC_{50}: (*Eisenia fetida*): 5.5/5.7 mg kg^{-1}	(Lofs-Holmin, 1981)
	LC_{50} (Field, *Apporectadea caliginosa*): < 1 mg kg^{-1}	
Biomass of earthworms	1800 g carb/ha (10 x recommended application rate)	(Förster et al., 1996)
	6.0 mg a.i. kg^{-1} (dry soil)	(van Gestel et al., 1992)
Reproduction rate of earthworms	>1.92 mg kg^{-1}	(van Gestel et al., 1992), (van Gestel, 1992)
Cocoon production (fertile cocoons)	EC_{50} (*Eisenia fetida*): 2.9 mg kg^{-1}	(van Gestel et al., 1992)
	>1.92 mg a.i. kg^{-1} (dry soil)	
	NOEC: 2.0 mg kg^{-1} (dry soil)	
Litter decomposition	1800 g carb/ha (10 x recommended application rate)	(Förster et al., 1996)
	18 mg m^2	(Eder et al., 1992)
	$NOEC_{50}$(Field): 0.24 mg kg^{-1} (Enchytraeids)	(Römbke and Federschmidt, 1995)

Table X23: Examples of critical loads proposed in literature with respect to physical characteristics and depending organisms (Horn, 1999)

Receptor	Critical load
Erosion	< 1 – 7 t · ha^{-1} · a^{-1} (specific or soil types)
Gas aeration	> 10 % ; 10^3 mg / m²h, O_2-depletion
Penetration resistance	< 1,5 - 3 MPa = 15 – 30 bar
Root growth	> 5 km · m^{-3} for sufficient H_2O-uptake
Apporectodea rosea	72,8 kPa axial, 230 kPa radial
Lumbricus terrestris	up to dB = 1,66 g · cm^{-3}
Apporectodea longa	up to dB = 1,50 g · cm^{-3}
Nematodes	< 1,20 g · cm^{-3}
Protozoa	< 1,55 g · cm^{-3}
Bacteria	< 1,70 g · cm^{-3}

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