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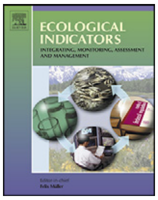

Soil ecosystem health and services – Evaluation of ecological indicators susceptible to chemical stressors

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ABSTRACT

The paper presents a methodological framework for quantifying soil ecosystem health with special focus on chemical stressors and ecological integrity as determinant for biological productivity of soil ecosystems. Ecological risk assessment is needed to facilitate the assessment of soil health and the capability of a soil to provide ecosystem services such as e.g. detoxification and decomposition of wastes, soil formation and renewal of soil fertility. We have developed such an approach that is based on systematic enumeration of vulnerable indicators that reflect essential soil ecosystem structures and processes that underlay such soil ecosystem services. The method is illustrated for a shortlist of common chemical stressors, represented by nickel, cadmium, chlorpyriphos, lindane and diazinon, and applied in a comparative assessment of suitability for use of grassland on contaminated soil. A comprehensive and relevant set of ecological integrity indicators has been analysed to derive a smaller core set of indicators highly relevant for all types of grassland use; i.e. reflecting ecological requirements to be fulfilled for any sustainable use of grassland.

1. Introduction

Biocapacity is the supply created by the biosphere, or a measure of the amount of biologically productive area available to provide the ecosystem services that humanity consumes. However, the quality of the goods and services provided depends on the quality of the supplying ecosystem (Mench et al., 2009). In Denmark, soil and food intake represent significant sources to children's exposure to lead (Pizzol et al., 2010) compared to lead exposure by inhalation. As such, soil quality criteria for different types of land use obviously must be (and can be) based on acceptable levels of human exposure to contaminants. Likewise, sustainable management practices restoring and maintaining soil ecosystem health in terms of suitability for use (i.e. the provision of ecosystem services) should be addressed; not only in term of quantitative above ground yields, but also services promoting the quality of air and water environments and maintaining plant and human health should be protected (Nielsen & Winding, 2002).

Within the methodological framework of the National Footprint Accountings (NFA), the ecological footprint and biocapacity are derived by multiplying the required and available bioproductive area with the ratio of national biological productivity of a specific land use type to the worlds average productivity of all land types included in the EFA framework (Ewing et al., 2010; Monfreda et al., 2004). According to Ewing et al. (2010), the biological capacity (biocapacity) represents the biosphere's ability to meet human demand for material consumption and waste disposal. However, as both ecological footprint and biocapacity are calculated from actual and above ground yields, the Ecological Footprint Analysis (EFA) fails to capture a biocapacity with reference to sustainable soil ecosystem health preserving yields.

We will not discuss of the equivalency factors (Kitzes et al., 2009) as these are empirical factors used for transforming required (EF) and available (BC) bioproductive land into units of global hectares and have been discussed elsewhere (e.g. Kitzes et al., 2009; Venetoulis & Talberth, 2008; Wiedmann & Lenzen, 2007; Wiedmann & Barrett, 2010).

Bioproductivity varies according to the inherent soil ecosystem characteristics, e.g. soil texture and soil organic matter and climate. This variation in time and space are verified by EFA studies using local yields for primary products at the sub-national level showing results varying by a factor of 2-10 (Haberl et al., 2001; Wiedmann & Lenzen, 2007).

At sub-national level, sustainable yields may be addressed in terms of sustainable and resource efficient management practices that balances carbon sequestering against the amount of harvested

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above ground NPP; securing that soil respiration does not exceed soil formation. Sustainable yields could be addressed by the biophysical quotient, i.e. the ratio of soil respiration (CO_2 efflux) to the residual soil C, describing the efficiency of substrate stabilization as an indicator of soil formation (Smith et al., 2007). Alternatively, by sustainable yields could be quantified at the level of no decline, or increase, in the in the below ground NPP (Dhital et al., 2010; Walsh et al., 2010).

The provision of soil ecosystem services such as fertile soil in terms of biological productive land is associated with soil ecosystem functioning, and is the result of interactions between soil biota and their chemical and physical environment. Soil ecological integrity is what provides biological productive land and there is a need for at least a minimum appreciation of soil ecosystem requirements to the soil microenvironment quality (Doran & Zeiss, 2000; Kamal et al., 2010; Spurlock et al., 2002; Sobolev & Begonia, 2008). Chemical, biological and physical soil quality aspects determining ecosystem productivity, such as below ground NPP, are totally absent in the EFA methodology (Venetoulis & Talberth, 2008). Therefore we present an overall framework for addressing soil ecosystem health, which may be used for defining local biocapacity estimates based on sustainable yields respecting ecological integrity.

As environmental stressors and soil management practices may impact the interactions between soil biota and their chemical and physical environment, soil health can be reduced and the provision of soil ecosystem services becomes limited. Opposite sustainable and intelligent resource efficient management practices may improve soil chemical and physical quality aspects supporting soil biota and i.e. soil formation and mitigate climate change as well as (e.g. Hodson, 2010; Lal, 2004; Mench et al., 2009; Tack and Meers, 2010; Tilman et al., 2006). Increased soil organic matter increases soil fertility and yields (Pan et al., 2006; Lal, 2004, 2008). Furthermore, an increase in soil organic matter improves water retention (inhibition of soil erosion), aeration, and other physical soil characteristics. To sustain soil ecosystem health therefore, one could say that the harvested NPP should not exceed the soil organic matter formation, which requires that anthropogenic emissions do not impact the biological component of soil ecosystem. With respect to contaminated soils, phytoremediation of the toxic metal content to an environmentally safe level (Koopmans et al., 2007; Tack & Meers, 2010) could be introduced as a chemical quality measure promoting the soil biological mass and i.e. soil formation.

This paper presents a conceptual system model for describing soil ecosystem health in terms of suitability for use (i.e. the provision of ecosystem services), with focus on deriving ecological indicators of ecosystem vulnerability to chemical stress. Impacts of chemical stress on biological diversity and land use impacts on soil fertility or health are complex matter difficult to quantify. Nonetheless, such impacts are the drivers for decreased habitat quality to a level that may exceed soil ecosystems ability to maintain the ecological processes and functions mediating waste assimilation and detoxification and i.e. productivity. A classification of vital ecological indicators enables a simple ranking analysis deriving a core set of vulnerability criteria. The relative susceptibility of soil ecosystems to chemical stressors may then be evaluated according to the derived vulnerability criteria. The conceptual system model and multi-criteria methodology is illustrated implementing the system model using defined ecosystem services as proxies for soil health. Our assumption is that if indicators reflecting ecological requirements for ecosystem services are not exposed beyond their no-effect concentration thresholds, the associated ecosystem service is not impacted. Vulnerability criteria for three types of grassland ecosystems are ranked and available data on multiple chemical stressors, i.e. nickel, cadmium, diazinon, lindane and chlorpyriphos, are discussed in terms ecological requirements. The system model may be used for the identification of high-concern areas in need of soil ecosystem health improving intervention measures, as well as for selection of relevant endpoints for site-specific ecological risk assessment.

2. Methodology

2.1. System model

A systematic approach for deriving scenario descriptions has been developed by Thomsen et al. (2006) and further improved in Sorensen et al. (2010) as a tool for defining worst case. In the present paper, this approach is illustrated for identifying highest-risk scenarios in respect to ecological requirements for land use on the basis of available toxicity data in the literature. Ecological requirements for land use are defined as conditions that need to be fulfilled in order for the soil ecosystem to provide the ecological services desired by society regarding a particular use of land.

The system model consists of the following sub-models:

1. *Model for problem analysis (Problem Decomposition Model, PDM).* Includes all sub-problems that may contribute to the cause of the risk problem; in this case-study preserving and enhancing the soil ecosystem services suggested to be based on a set of ecological requirements for land use and associated ecological indicators.
2. *Model for scenario composition (Scenario Composition Model, SCM).* Estimates a reduced set of sub-problems assumed to reflect the most important aspects in relation to highest risk conditions. In this case-study, soil ecosystem health sub-problems identified as ecological indicators susceptible to chemical stressors.
3. *Model for criteria setting (Criteria Model, CM).* Finds analogies between the sets of sub-problems included in SCM and data sets that will form criteria of higher/lower risk condition; in this case-study, quantification of sub-problems susceptible to chemical stressors by eco-toxicological data sets as approximations of sub-problems in *SCM*.
4. *Model for scenario selection (Scenario Selection Model, SSM).* Predicts the highest risk scenarios based on the criteria values; in this case-study vulnerability criterion with respect to chemical stressors.
5. *Model for risk quantification (Risk Quantification Model, RQM).* Predicts the risk level for each of the selected scenarios.

The present work describes step 1 in general terms, with focus on step 2, 3 and 4. Step 5 may be addressed in soil health scenario analyses for setting up quality criteria for long term sustainability of soil ecosystem services. As such, the system model may be used for deriving ecological indicators vital for future soil ecosystem health assessment, decision support for soil ecosystem health management; and, where needed, soil health improving intervention strategies for securing long-term fertility and i.e. productivity of land. Details regarding the System Model Approach and an in depth description of the derived ecological indicators may be found in Thomsen et al. (2006).

2.2. Implementation of the system model using ecosystem services as proxies for soil health

2.2.1. Problem Decomposition Model

Below, ecosystem services are listed and subdivided into ecological requirements and associated ecological indicators. Ecological indicators susceptible to chemical stressors are of relevance for the identification of specific eco-toxicological data used as input data in the multi-criteria model used for estimating worst-case

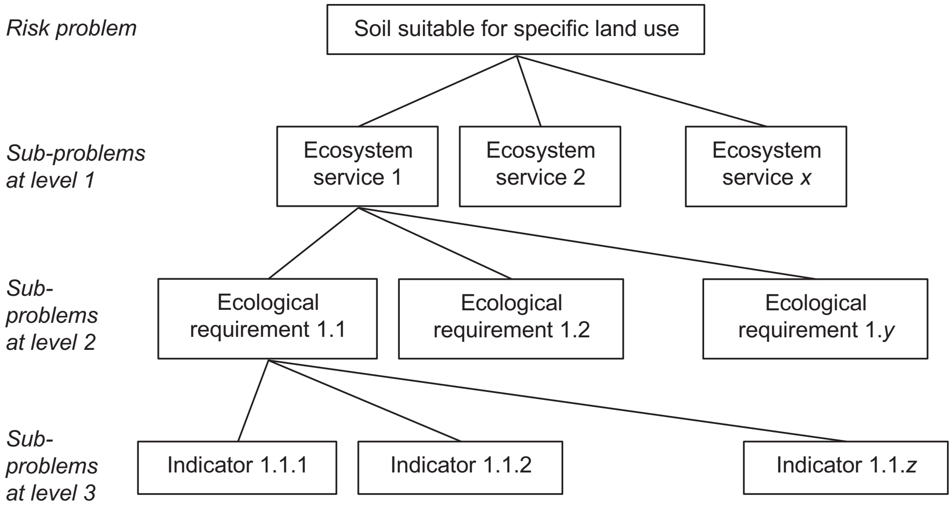

Fig. 1. Problem tree configuration for soil ecosystem health in terms of ecological suitability for specific land use, depicted as ecosystem services subdivided into ecological requirements down into ecological indicators representing ecosystem structure and functioning, biodiversity and soil processes that are needed for the provision of soil ecosystem services.

scenarios for subsequent soil ecosystem health assessment. The Problem Decomposition Model for the preservation and enhancement of soil ecosystem health may be illustrated for every type of land use, as in Fig. 1, following the stepwise approach of a problem tree (Thomsen et al., 2006).

The main purpose of the Problem Tree is to obtain a systematic description of the risk scenarios, sub-problems, known and unknown knowledge and data gaps by purpose of being able to describe the restrictions and conditions for a given final quantitative risk estimate. The outcome of the risk scenario description is, to the best of knowledge, the most important aspects, i.e. sub-problems, to be addressed within a risk assessment able to respect the ecosystem requirements needed for to maintain the provision of soil ecosystem services.

2.2.1.1. Risk problem: suitability for land use. Risk assessment of contaminated land may focus on ecological suitability for land use. Scenario analysis for the purpose of pre-selecting high risk scenarios for risk assessment can be attuned for any type of land use. Focus may be on different land use categories; in this case-study agricultural (dairy farming), “nature” (meadow), and urban (recreational grassland). Any soil ecosystem health scenario analysis and risk quantification will gain in accuracy by precise definition of land use and goals for use.

2.2.1.2. Sub-problems at level 1: ecosystem services. Soil ecosystem health is not easily expressed in well-defined representative measurable sub-problems, i.e. biological, physical and chemical key parameters that need to be protected for the soil ecosystem service system to survive. Because of the complexity of the soil ecosystem, ecological indicators might not be available at all. However, the degree of fulfilment of ecosystem services may be used as proxies for ecosystem health (TCB, 2003; Breure, 2004).

The following set of soil ecosystem services were recognised as relevant for all open types of land use (after TCB, 2003; MA, 2005):

(A) Soil fertility, the capacity to provide nutrients and biomass;
(B) Adaptability and resilience, the capacity to adapt, or the fragility upon disturbance and changes in land use;
(C) Buffer and reaction function, storage and buffering of water, gasses, chemicals, energy, cation exchange capacity, breakdown and synthesis of chemicals (detoxification, humification)
(D) Disease suppression and pest resistance, the natural capacity to prevent and suppress pests and diseases
(E) Habitat and biodiversity, genetic, functional and structural;
(F) Physical support; supportive capacity, historical archive, landscape identity.

2.2.1.3. Sub-problems at level 2: ecological requirements. Ecological requirements may be defined for the above listed ecosystem services. Ecological requirements are the actual structures or processes of the ecosystem that underlie ecosystem services; they require a minimum level (qualitative or quantitative) in order for the ecosystem to function properly. In other words, for ecosystem services to be provided to society, a certain level of soil quality is required. Soil fertility, e.g. decomposition processes (fragmentation, mineralisation, humification), requires different functional groups of soil biota (cf. Table 1). The actual condition of ecological requirements may be assessed using proper indicators representing these functional groups.

2.2.1.4. Sub-problems at level 3: ecological indicators. Indicators were denominated as potential means to assess the state of ecological requirements; they may include indicators for soil biota, soil processes, or conditions of ecological sustainability. Numerous ecological indicators may be conceived; preference was given to those that have been used in toxicity testing in the field or in the laboratory. Indicators for ecological requirements were assessed for susceptibility for chemical pressure (yes/no) and, if affirmative, eco-toxicity data were searched for in the literature and Internet databases (Thomsen et al., 2006; De Lange et al., 2006). Compounds included in this study are: nickel, cadmium, chlorpyriphos, lindane and diazinon.

2.2.2. Scenario composition model

Table 1 represents the scenario composition model with regard to sub-problems susceptible to chemical stress (Thomsen et al., 2006). The first column represents the above listed six ecosystem services, sub-divided into individual aspects of ecological requirements, i.e. sub-problems at level 2, which are sub-divided into ecological indicators susceptible to chemical stressors, at sub-problem level 3.

Table 1
Sub-problems at level 1, 2 and 3 of the problem tree. Grey cells in the third column represent ecological indicators for which data are available for the five case-study compounds nickel, cadmium, chlorpyriphos, lindane, and diazinon.

Sub-problems at level 1: ecosystem service	Sub-problems at level 2: ecological requirements	Sub-problems at level 3: susceptible ecological indicators	
Soil fertility	General biodiversity aspects	1	Biodiversity indices
	Microbial aspects	2	Arginine deaminase activity
		3	Carbon sources utilization diversity
		4	Cellulase activity
		5	Microbial biomass and activity
		6	Mycorrhizal infestation
		7	Nitrification
		8	Phosphatase activity
		9	Soil respiration
		10	Sulphur oxidation
		11	Urease activity
	Plant aspects	12	Dicotyledons biomass (fodder quality)
		13	N content (fodder quality)
		14	Litter standing crop
		15	Root density
		16	Root turnover
		17	Vegetation biomass
		18	Vegetation standing crop
	Fauna aspects	19	Anecic earthworms
		20	Ants
		21	Cattle meat quality
		22	Collembola
		23	Earthworm community structure
		24	Earthworms
		25	Epigeic earthworms
		26	Hoverflies, other dipterans, beetles
		27	Isopods
		28	Millipedes
		29	Mites
		30	Native bees
		31	Nematode community composition
		32	Nematodes
		33	Pollinators
		34	Protozoa
		35	Slugs, snails, beetles
		36	Springtails
		37	Springtails, mites
	Physical/chemical aspects	38	Ionic strength
		39	Loss on ignition
		40	Soil aggregates
		41	Soil bulk density
Adaptability and resilience	Fauna aspects	42	Earthworm ecological groups
		43	Mites functional groups
		44	Nematode community structure
		45	Oribatid mites
	General biodiversity aspects	46	Diversity indices
		47	Rank abundance distribution
		48	Soil food web complexity
	Microbial aspects	49	Fungi:bacteria ratio
		50	Nucleic acids microbial population characterization
Buffer and reaction	Fauna aspects	51	Anecic earthworms
		52	Earthworm bioturbation activity
		53	Epigeic and endogeic earthworms
	Microbial aspects	54	Carbon sources utilization diversity
		55	Methanotrophic diversity
	Physical/chemical aspects	56	Loss on ignition
		57	Soil organic matter
	Plant aspects	58	Litter standing crop
		59	Primary production
		60	Root turnover
		61	Tree growth
		62	Vegetation standing crop
Disease suppression	Fauna aspects	63	Predator species diversity
	General biodiversity aspects	64	Green vein landscape elements
		65	Key species
	Microbial aspects	66	Antibiotics producers
Biodiversity	General biodiversity aspects	67	Diversity indices
		68	Growth form diversity
		69	Isoenzymes
		70	Key stone species
		71	Species diversity
	Microbial aspects	72	Nucleic acids microbial population characterization
Physical support	General biodiversity aspects	73	Vegetation cover
	Physical/chemical aspects	74	Soil aggregates
		75	Soil bulk density
		76	Soil stratification
	Plant aspects	77	Root density

Table 2
Data set quantifying of sub-problems at level 3 (see also Thomsen et al., 2006; De Lange et al., 2006). Toxicity threshold concentrations in [mg/kg dry wt]. (A), no observed effect concentrations; (B) toxicity effect concentrations in mg/kg dry wt soil.

Ecological indicators, sub-problem level 3			Microbial biomass and activity	Soil respiration	Anecic earthworms	Collembola	Earthworms	Epigeic earthworms	Springtails	Springtails, mites	Earthworm ecological groups	Anecic earthworms	Epigeic and endogeic earthworms	Key species	Key stone species
		ID	5	9	19	22	24	25	36	37	42	51	53	65	70
A	Cadmium	Max		450	250	350	250	130	350	350	250	250	130	250	250
	Chlorpyrifos		0.0146	10			100	100	0.065		5		117.4	10	10
	Diazinon					0.25			0.25					8.71	8.71
	Lindane						29		0.056		29		29	32	32
	Nickel			9685		800	700	700	800	800	700		700	700	700
	Cadmium	Median		160	250	66	22.5	19	66	43	22.5	250	19	14	14
	Chlorpyrifos		0.0146	10			40	4.6	0.065		100	0	4.6	4.6	4.6
	Diazinon					0.25			0.25					4.48	4.48
	Lindane						12		0.053		12		12	10	10
	Nickel			461		645	110	110	645	645	110		110	110	110
	Cadmium	Min		63	250	2.9	5.3	5.3	2.9	2.9	5.3	250	5.3	1.7	1.7
	Chlorpyrifos		0.0146	10			2.6	2.6	0.065		4.6	0	2.6	2.6	2.6
	Diazinon					0.25			0.25					0.25	0.25
	Lindane						3.2		0.032		3.2		3.2	0.032	0.032
	Nickel			280		173	65	65	173	173	65		65	65	65
B	Cadmium	Max													
	Chlorpyrifos		10		77.8		117.4	117.4	0.26		117.4	77.8	117.4	100	100
	Diazinon				233	0.7	233	130	0.7		233	233	130	233	233
	Lindane				40.4		465		2.21		399	40.4	399	399	399
	Nickel					476	883	883	476	476	883		883	883	883
	Cadmium	Median													
	Chlorpyrifos		10		61.8		70.8	11.65	0.056		11.65	61.8	0.3	11.65	11.65
	Diazinon				59	0.7	94.5	130	0.7		94.5	59	130	4.3	4.7
	Lindane				40.4		40.4		0.1815		40.4	40.4	40.4	30.2	30.2
	Nickel					476	622.5	622.5	476	476	622.5		622.5	622.5	622.5
	Cadmium	Min													
	Chlorpyrifos		0.0146		45.8		0.3	0.3	0.017		0.3	45.8	0.3	10	10
	Diazinon				32	0.7	32	130	0.7		32	32	130	0.7	0.7
	Lindane				40.4		1.9		0.0936		1.9	40.4	1.9	0.0936	0.0936
	Nickel					476	362	362	476	476	362		362	362	362

Table 3

Relative importance of 77 ecological indicators listed in Table 1 (same IDs), i.e. criteria, for three types of grassland use. Relevancy scores: 2, highly relevant; 1, minor relevancy; 0, irrelevant.

ID	Susceptible ecological indicator[a]	Grassland use		
		Dairy farming	Natural meadow	Recreational
1	Biodiversity indices	1	2	0
2	Arginine deaminase activity	1	1	0
3	Carbon sources utilization diversity	2	2	1
4	Cellulase activity	2	2	1
5	Microbial biomass and activity	2	2	1
6	Mycorrhizal infestation	2	2	1
7	Nitrification	2	2	2
8	Phosphatase activity	2	2	1
9	Soil respiration	2	2	1
10	Sulphur oxidation	1	2	1
11	Urease activity	2	2	2
12	Dicotyledons biomass	1	2	1
13	N content (fodder quality)	2	1	0
14	Litter standing crop	1	2	1
15	Root density	2	2	2
16	Root turnover	2	2	1
17	Vegetation biomass	0	2	1
18	Vegetation standing crop	2	2	1
19	Anecic earthworms	2	2	1
20	Ants	1	2	0
21	Cattle meat quality	2	1	0
22	Collembola	1	2	0
23	Earthworm community structure	2	2	1
24	Earthworms	2	2	1
25	Epigeic earthworms	2	2	1
26	Hoverflies, other dipterans, beetles	2	2	0
27	Isopods	1	2	0
28	Millipedes	0	2	0
29	Mites	2	2	1
30	Native bees	1	2	0
31	Nematode community composition	2	2	1
32	Nematodes	2	2	1
33	Pollinators	1	2	1
34	Protozoa	2	2	1
35	Slugs, snails, beetles	1	2	1
36	Springtails	1	2	1
37	Springtails, mites	1	2	1
38	Ionic strength	2	2	1
39	Loss on ignition	2	2	2
40	Soil aggregates	2	2	2
41	Soil bulk density	2	2	2
42	Earthworm ecological groups	2	2	1
43	Mites functional groups	2	2	1
44	Nematode community structure	2	2	1
45	Oribatid mites	2	2	1
46	Diversity indices	2	2	1
47	Rank abundance distribution	2	2	0
48	Soil food web complexity	2	2	1
49	Fungi:bacteria ratio	2	2	1
50	Nucleic acids microbial population characterization	2	2	1
51	Anecic earthworms	2	2	1
52	Earthworm bioturbation activity	2	2	1
53	Epigeic and endogeic earthworms	2	2	1
54	Carbon sources utilization diversity	2	2	1
55	Methanotrophic diversity	1	1	0
56	Loss on ignition	2	2	1
57	Soil organic matter	2	2	1
58	Litter standing crop	2	2	1
59	Primary production	2	2	1
60	Root turnover	2	2	1
61	Tree growth	1	1	1
62	Vegetation standing crop	2	2	1
63	Predator species diversity	1	2	0
64	Green vein landscape elements	1	1	0
65	Key species	2	1	0
66	Antibiotics producers	1	1	0
67	Diversity indices	1	2	1
68	Growth form diversity	1	2	0
69	Isoenzymes	0	2	0
70	Key stone species	1	2	0
71	Species diversity	2	2	1
72	Nucleic acids microbial population characterization	2	2	1
73	Vegetation cover	2	2	1

Table 3 (*Continued*)

ID	Susceptible ecological indicator[a]	Grassland use		
		Dairy farming	Natural meadow	Recreational
74	Soil aggregates	2	2	1
75	Soil bulk density	2	2	2
76	Soil stratification	1	2	0
77	Root density	2	2	2

[a] Estimated relevance of ecological indicators sensitive to chemical stressors for grassland ecosystems in relation to typical examples for land use: agricultural (dairy farming), “nature” (meadow), and urban (recreational grassland). Ecological indicators were ordered by soil ecosystem service and basic aspects of the ecosystem.

Table 4
Classification of 77 ecological indicators into equivalent weight classes. Cr_1, Cr_2, Cr_3: respective criteria values for dairy grassland, natural meadow and recreational grassland; 2, highly relevant; 1, minor relevancy; 0, irrelevant. ID numbers in bold represent ecological indicators for which data are available.

Grassland type relevancy criteria (Cr_1,Cr_2,Cr_3)	susceptible indicators with Equivalent weight	
	No toxicity data available	Toxicity data available
(2,2,2)	11, 15, 39, 40, 41, 75, 77	
(2,2,1)	4, 6, 8, 16, 18, 23, 29, 31, 32, 34, 38, 43, 44, 45, 46, 48, 49, 50, 52, 54, 56, 57, 58, 59, 60, 62, 71, 72, 73, 74	**5**, **9**, **19**, **24**, **25**, **42**, **51**, **53**
(1,2,1)	12, 14, 33, 35, 67	**36**, **37**
(2,2,0)	47	
(2,1,0)	13, 21	**65**
(1,2,0)	20, 27, 30, 63, 68, 76	**22**, **70**
(1,1,0)	55, 64, 66	
(0,2,0)	69	

2.2.3. *Toxicity data*

Criterion data sets, i.e. toxicological data as approximations of ecological indicators susceptible to chemical stress, are presented in Table 2, depicting toxicity data from field and laboratory studies. Descriptive statistics for the two data sets are presented as minimum (Min), median (Median) and maximum (Max) concentrations.

Toxicity data may be used for ranking soil heath risk scenarios in the scenario selection model, as well as in consecutive risk assessment for the derivation of soil quality parameters needed to fulfil the defined ecological requirements.

If no toxicity threshold data are available in the literature, then a data gap exists. When no criterion data for the approximation of ecological indicators for a sub-problem at level 2 exit, then this sub-problem is left out of subsequent analysis, leading to increased ignorance and, thus, basic uncertainty. An example from the present case-study is missing data on any of the ecological indicators quantifying impacts of chemical stressors on affecting ecological requirements related to plant aspects.

It is also possible to identify basic uncertainty if only a very limited number of the ecological indicators for a sub-problem are covered by data. An example from the present case-study is microbial aspects of ecological requirements which are poorly covered; e.g. no data on impacts of chemical stress on two genera of bacteria vital for soil nitrification, a central process in the nitrogen cycle related to soil fertility, are available for any of the five case-study compounds. Thus, the degree of completeness in data for quantification of the ecological indicators listed in Table 1 is highly important for soil ecosystem health assessment as a part of a complete uncertainty assessment.

2.2.4. *Criteria model*

2.2.4.1. Data on the importance of selected ecological indicators. Soils may, in general, provide a number of ecosystem services, and depending on the intentional land use, some of these may be considered more relevant than others. In the present section, a systematic approach of describing soil health scenarios in terms of basic criteria for soil ecosystem functioning are presented. Therefore, a tentative classification of soil health criteria is presented in terms of their relevance to land use. For illustration purposes, a limited selection of land use types is presented. This classification into land uses and ecosystem services may serve as a basis to recognise vulnerable and sensitive structures and processes in ecosystems that are needed in the provision of ecosystem services. Eventually, in subsequent risk assessment, soil quality standards may be developed for chemicals with potential impact on soil health (the main risk problem) through definition of toxicity thresholds to safeguard sustainable land use. In Table 3, the basic criteria for soil ecosystem functioning are listed. In addition, the relative importance is given according to expert judgement of soil ecosystem requirements in view of three types of grassland use.

3. Results and discussion

A critical issue is to find a reduced core set of the 77 ecological indicators listed in Table 2. It is also a critical issue to assess whether available data cover the most important indicators. So, the first step is simply to group the ecological indicators in clusters of similar importance, i.e. equivalent weights, for all three types of ecosystem services, as presented in Table 4. The next step is to assess the data coverage for the most important ecological indicators.

A comparison between Tables 3 and 4 shows that for the core set of ecological indicators having the highest score of 2 for all three types of grassland no ecological indicator is covered with data. The data coverage improves if it is assumed that urban grassland soil ecosystem health is of less importance for the provision of associated soil ecosystem services than dairy farming and natural meadows. In this case, (2,2,1) scoring includes 8 ecological indicators for which the impact of chemicals stressor are covered by data. In general, little knowledge on the impact of chemical stressors on soil health is available, and uncertainty from such data gaps is therefore highly critical.

3.1. *Concluding remarks*

We have developed an approach that is based on systematic enumeration of vulnerable indicators that reflect essential soil ecosystem structures and processes that underlay soil ecosystem services. The method is illustrated for a shortlist of common chemical stressors, for which toxicity data are relatively well-available in the scientific literature, and applied in a comparative assessment of suitability for use of grassland on contaminated soil under various types of land use. A comprehensive and relevant set of ecological indicators has been analysed to derive a smaller core set of indicators highly relevant for all types of grassland use; i.e. reflecting ecological requirements to be fulfilled for any sustainable use of grassland. However, available data to assess the sensitivity to chemical stressors reveal critical data gaps. While this is limiting any analytical and theoretical approach for soil health assessment to evaluate soil preservation, management and legislation, the systematic enumeration of indicators will illustrate ignorance and facilitate uncertainty assessment.

Soil fertility is an important and complex ecosystem service; a large set of indicators was enumerated, clearly outnumbering any listing for other ecosystem services. This is perhaps a result of bias from available knowledge or personal experience. However, too many indicators are not a problem, but too few might be, as it can result in ignorance from data gaps. Would these be critical data gaps? How can we know this? Perhaps soil biology has focused upon the most important aspects in past decades to overview at least the very largest part of important soil health criteria. But again, how can we know this? On the other hand: it is hard or perhaps impossible to identify missing criteria. We have disclosed some: actinomycetes, autotrophic bacteria, pollinating insects with soil dwelling larvae (e.g. some hoverflies and beetles), lichens, and other symbionts, and faunistic and floristic genetic diversity. Some of these indicators are thought to have minor contributions to ecosystem services (which is probably a reason for not being studied by ecotoxicologists). There is misrepresentation of plant ecological indicators, except perhaps for primary production under soil fertility. Although this is a clear omission, this may not jeopardize risk assessment scenarios much, as plants are not considered to be most sensitive to the chemicals assessed here.

A loss of any component of sustainable ecosystems is not captured by biocapacity measured in terms of productivity as long as prevailing conditions sustains increased yields by substitute inputs to the system (Carter, 2002; Mózner et al., 2011). Therefore, a precautionary approach could be used to define maximum ecological productivity appreciating some level of soil ecosystem requirements needed for maintaining ecological integrity (Harris, 2009). Knowledge of soil ecosystem requirements may guide the planning of health improving soil management practices (e.g. Khan, 2005; Koopmans et al., 2007; Lugato et al., 2006) and future site specific sustainable land management to be accounted for in Ecological Footprint Analysis (Bastianoni et al., 2011; Kissinger and Gottlieb, 2011; Wiedmann & Barrett, 2010). Maintenance or restoring of grassland soil ecosystem health may play a significant role in climate change mitigation by enhanced soil carbon sequestration and reduced soil respiration or CO_2 efflux (Conant, 2010; Zhang et al., 2010).

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