A Biological Indicator for Soil Quality

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Introduction

There is a growing interest in instruments to assess the present and to predict the future performance of ecosystems that are or may be influenced by human activities. Keywords in this respect are ‘sustainable development’ (World Commission on Environment and Development 1987) and ‘sustainable use of biodiversity’ (UNCED 1992). Apart from the intrinsic value of biodiversity, there are several reasons to preserve biodiversity from a functional point of view: The information functions, the production functions and the life support functions of biodiversity (European Commission 1998). An important life support function is the functioning of soil. Within agro-ecosystems this function can be seen as a production support function of biodiversity, next to e.g. pollination and natural pest control. Governmental concern is growing how to attain a sustainable use of ecosystems, e.g. the agricultural use of soils. Is an aboveground species-based approach sufficiently predictive for future ecosystem performance? Are sufficient numbers and types of species addressed? The still open answers to these questions have led the Dutch government to initiate research to develop an biological indicator for soil quality (BISQ), as an activity related to the Treaty on Biological Diversity adopted in Rio de Janeiro (UNCED 1992).

Outline and Aims

A proper soil functioning now and in the future is a key life support function (Brussaard et al 1997, Schulze and Mooney 1994). This paper presents an outline of a project in which an indicator system for biological soil quality is developed that can be applied both in diagnostic and in prognostic approaches, and can be measured within a soil-monitoring network. Additionally, some ways to integrate detailed soil biological parameters into an aggregated presentation format are presented. Possible choice problems, like the choice of a proper reference or policy target, are discussed.

The choices on operational parameters for Life Support Functions (LSF)

The indicator system aimed at should produce an integrated view of the “ecological state” of the soil relative to a desired or optimal situation, with respect to a series of specific LSF functions of soil (such as production, mineralisation, nutrient cycling, etc.).

Soil organisms are assumed to be directly responsible for soil ecosystem processes, especially the decomposition of soil organic matter and the cycling of nutrients (Wardle and Giller 1997). These processes are regarded as major components in the global cycling of materials, energy and nutrients. For example, the soil biomass (25 cm top soil layer) is known to process over 100,000 kg of fresh organic material each year per hectare in many agricultural systems. This processing includes the decomposition of dead organic matter by the microbes as well as the consumption and production rates in the soil community food web. From the viewpoint of functional biodiversity, an indicator for soil life support functions could best be based on the measurement of processes. However, soil processes fluctuate strongly in time and space. Establishing a mean annual value of a process requires an intensive sampling programme, and is difficult to realise on a national scale. Therefore it is more practical to use the species composition, aggregated in functional groups, as an indicator for the capability of processes. However, the relationship between species composition and ecosystem functioning is difficult to quantify. When species disappear, others can become more dominant and take over a link in the process. It is possible that a process will continue while species composition has changed or degraded. So the preservation of biodiversity can not be guaranteed solely by measuring process values. Many processes are too general or insensitive as an early warning indicator.

In general, heavy pollution or disturbances select for a few resistant species. In such situations the ecological basis for processes may become very narrow. When the resistant species also disappear, or are inhibited, as a result of future and yet unknown human activities a process stops and the life support function is permanently affected. Therefore, we based the indicator system for life support functions of the soil on the following hypothesis: *The threat of vital soil processes can be expressed by comparing the number of species in functional groups of a certain area with its reference (undisturbed locations).*

Due to redundancy of species, a process is assumed to continue to exist with fewer species, when species disappear, in which case the risk of instability and uncontrolled fluctuations will increase.

Schouten et al. (1997) surveyed important functions and processes in soil and the organisms involved. Since the indicator system is designed from a functional point of view, a selection of soil organisms had to be related to the most important life support functions. Moreover, the aim was to obtain a representative view (section) of the soil ecosystem, in which a food web model for the quantification of several life support functions could be used (De Ruiter et al 1993, 1995). Processes belonging to these functions were then listed, including the responsible groups of organisms. The ultimate indicators were chosen on the basis of a criteria list of for example: possibilities for measurement in a monitoring programme, sampling ease, costs of analysis, and diversity of species and functional groups. The selection procedure resulted in a set of 12 indicative variables. These variables give indicators based on diversity within functional groups, a number of bacterial degradation routes and model predictions about nitrogen mineralisation from the food web and system stability. The indicator system is summarised in Table 1.

The indicators in the system are the result of a stepwise selection process. This selection in combination with the functional approach ends up in an incomplete cross-section through the soil ecosystem. The individual indicators have a qualitative character. Integration of data from the different indicators into a food web model enables quantification of (the LSF) nutrient mineralisation, in this case specified for nitrogen (no. 6 in Table 1). Based on the same measurements the stability and resilience of the system can be calculated (no 12 in Table 1).

There is not an easy policy or solution for the life support approach for (soil) biodiversity conservation, even on a scale of a small country like the Netherlands. The belowground quality of life support functions can be described by the more traditional total soil fauna diversity. However, in the ecological approach of analysing, the species composition of all taxonomic groups, completed with numbers, biomass and activity for food web modelling, is hardly applicable on a national scale. On the other hand, the biochemical approach with direct measurements of processes is too general and asks intensive sampling campaigns in time and space.
The indicator system presented in this report tries to give the golden mean, which can practically be realised. With the knowledge and expertise available in several Dutch institutes and universities, the indicator system can be accomplished. The Dutch Soil Quality Network (DSQN), a national monitoring network of the RIVM (200 locations), offers a usable infrastructure, and the advantage of available comprehensive abiotic measurements. The combination of biotic and abiotic measurements in the same monitoring programme leads to the possibility of deducing response models for the individual indicators. With such models based on the dataset obtained, predictions can be made about effects of environmental and human impact scenarios. Insight in the relation between abiotic conditions, management practices and the composition and functioning of the soil food web offers opportunities to adapt political and

management practices towards optimal (sustainable) use of the soil biodiversity and the ecological processes that are governed by soil organisms.

To establish the scale on which indicators fluctuate, it is necessary to make reference descriptions and determine effects of severe disturbances. This gives a yardstick to judge the seriousness of a given situation.

The measurement of the number of taxonomic groups or processes in the indicator system may be minimised. However, almost in every case this leads to a reduction in the variety of life support functions covered, or the loss of the possibility of food web modelling.

From a scientific and pragmatic point of view, the life support concept can be an operational approach for the protection and sustainable use of soil biodiversity. Policy goals can be formulated on the basis of deviation from a chosen reference situation. Realisation of the indicator system depends on the need of information, the available finances, and the control through research programmes by the ministries involved.

For pragmatic reasons, the following processes were selected as a starting point for indicator development:

- Fragmentation and degradation of organic material,
- Recycling and availability of nutrients (e.g. nitrogen mineralisation),
- Soil structure evolution (bioturbation and aggregate formation),
- Stability of ecosystems (and related food webs).

Indicative variables, basic to the integrated indicator, are potential rates of various processes, food web structure, and diversity within and abundance of functional groups of organisms. Currently, the indicator system contains 12 distinct indicative variables, which may contain several derived indicators**.** These variables and (calculated) indicators can be integrated in a circular histogram (amoeba) plot or a single-digit soil quality index (SQI). Spatial or temporal changes will appear as a changed amoeba-shape, or an increased or decreased index value.

Since 1997 a survey has been performed based on the infrastructure of the DSQN, a monitoring network designed to obtain policy information regarding abiotic soil status trends. DSQN covers a sample selection of 70 % of the surface area of the Netherlands, and a complete sampling ‘round’ takes five successive years. Until 2001 about 120 plots within the network have been sampled. The additional biotic variables measured were: abundance and diversity of nematodes, earthworms, and enchytreads, nitrifying activity, diversity of microbial functions (using community level functional profiles based on the Biolog-system as described in Rutgers and Breure (1999), and total activity and numbers of bacteria. Identification of the mite fauna and complete food web sampling were performed on a limited number of sites. The DSQN data on chemical soil composition were used to relate the occurence of organisms to abiotic conditions and land-use. To obtain insight into the 'length of the scales' for each parameter, 50 additional plots from outside the network have been sampled, such as biological farms, nature areas and polluted areas. All biotic and abiotic data are collected in a database.

Results

So far the database contains samples obtained from dairy farms on sandy soil and marine clay, arable farming, horticulture farms, and several nature areas. Most indicators are significantly different between the investigated soil types and/or land-use forms. Indicator values in two land-use types (grasslands on marine clay and horticulture) are summarised in Table 2. Both land-use types represent conventional (relatively intensive) agricultural land-use. In addition, to present a provisional idea on the role of reference areas in the indicator system the network data were compared to data collected at an extensively managed grassland site. Most indicator values were highest at this reference site. Thus, it can be concluded that the 'length of the indicator ruler' is sufficient to distinguish between soil types, and within soil types between land-use (grasslands different intensities of farming).
To obtain insight into the discriminative power of the results between intensive and extensive management of soil, we used the data derived from 70 dairy farms on sandy soil, and investigated the effects of management practices on soil fauna composition.
A result is shown in Figure 1, where the number of nematode taxa is shown as a function of the amount of cattle units per hectare, here given as cattle unit: the amount of cattle, excreting 41.kg nitrogen per year. It is clear that many taxa get lost when fertilisation increases. Further analysis of the data yields, that the total amount of individuals of nematodes (total abundance) remains unaltered over a long range of land-use intensities, but the species diversity decreases, indicating decreased ecosystem stability as a result of increased management intensity.

Communication of results

Diagnostic approach

Results, if any, should be communicated to policy makers and the public in an unambiguous and clear way. This asks for two further incentives, the first to prove that the indicator is indeed indicative for the policy problem at hand, and this may appear from further work. The second issue has been given some thought, using developments in related fields.

The results from Table 2 can be presented a clear and illustrative way for diagnostic purposes as shown in Figure 2. This method results in an amoeba, a circular histogram plot representing all indicator values, scaled against a historical, undisturbed, or desired situation. The establishment of a proper reference, probably per soil type, will be part of future efforts, but for the purpose of illustration the indicator data from a biological grassland plot were used as a reference for the intensively used plots (Figure 2).
Each reference variable was scaled as 100 %. This yields a circle of 100%-values for the reference location. In the example, mite fauna and total food web structure were omitted due to lack of data from the reference. The indicative parameters appeared almost all within the 100%-circle. Apparently, biodiversity within functional groups, and process rates were lower in intensive than in the extensive plots. Only bacterial biomass is very high (312 %), which is reflected in the diversity of bacterial feeding nematodes (126 %). Despite the high bacterial biomass, its activity (indicated by the number of colony forming units, nitrifying activity and ^{14}C-leucine and ^{3}H-thymidine incorporation) is approximately 90 % of the reference, so the specific activity is lower.
The indexed indicator values used to construct the graph can be further aggregated into a SQI using the average factorial deviation of the reference value. In this SQI a value of 50 % has the same weight as one of 200 % of the reference value (both a factor 2). For the example-amoeba, this exercise resulted in an SQI value of 65 % for the regular farms versus the biological farm. This SQI might be used in the assessment of a Natural Capital Index, as proposed by Ten Brink (1998).

Prognostic approach

For prognostic purposes, habitat response relationships for soil organisms are derived using multivariate regression techniques. The occurrence of species in any ecosystem strongly depends on a variety of habitat criteria in terms of compatible physicochemical conditions, which includes acceptable environmental toxicity.
The development of such multi-stress ecosystem models has recently begun. At the moment the presence, absence, and abundance of species in The Netherlands may be expressed as a function of soil and vegetation type, nitrogen and water availability, soil acidity and salinity, clay content of the soil, heavy metal concentration and management details. As a demonstration of the first results of this effort, Figure 3 shows the relationships of the presence of 100 different taxa of nematodes and the soil pH, given that all the other abiotic parameters are fixed on their average values. This effort uses the data obtained in the BISQ data collection programme for prognostic purposes. From this figure it is clear, that the presence of organisms may increase, decrease, and stay constant as a result of environmental changes: each species has its own sensitivity, and one cannot simply say: if pH increases biodiversity goes in this or that direction.

When information on abiotic conditions is available these multivariate habitat-response relationships between the presence of organisms and the abiotic soil parameters can be used in a geographical information system to predict the presence of soil organisms on a regional and national scale, as is shown in Figure 4.

Given the environmental quality that is expected to result from future policy decisions, the data obtained in this study can be used to predict future effects on soil functions and possibly on sustainability of soil use. A scenario in which intensified agricultural land use is foreseen might show that life support functions (LSF) will still exist but will be less stable, which might be due, for example, to reductions in the number of species in functional groups. On the other hand, if action were sought to maximise sustainability, the number of species executing certain tasks (within-functional group species diversity) would have to be maximised, which would generate critical limits on various land use parameters.

As mentioned earlier, the BISQ is based on a static food web model. Given the amounts of species within the different functional groups, it can be used to calculate the maximal carbon and nitrogen mineralisation rate of the system.

It is our aim, to incorporate the habitat-response relationships obtained for the different taxa into the food web model in order to make it dynamic and to be able to calculate different scenarios and to predict the effects of different types of soil management.

Conclusions

It was shown that the selected indicators differed significantly between the different DSQN- categories. As an example of ecological soil quality assessment, an 'amoeba-presentation' was made of the grasslands with a biological farm used as a reference. The amoeba-presentation is a way to judge biodiversity changes in relation to a functional background. The quality can also be expressed in a SQI. Of course the value of such an index depends on the indicators taken into account. Also the reference is likely to be different for different types of soil ecosystems.

Issues of concern are still to be solved, existing lines of research can address some of these. For example, the quantitative relation between biodiversity and soil LSF's remains to be established. Some essential soil processes can be addressed using food web modelling (e.g., De Ruiter et al., 1995), in which structural diversity and functions can be linked. However, the validation of a soil food web model requires data on structure and biomass of functional groups.

For prognostic assessment of soil quality the model must be developed based on multivariate descriptions of the biotic (response) data as mathematical functions of the abiotic (cause) data, that will eventually result from a sufficient (number, representing all main Dutch soil use types) sampling and analysing effort. Based on the variation in the collected data, it was estimated that the soil samples necessary to construct reasonably reliable response equations, are at least two hundreds. The mathematical relations to be generated can be used to predict the effects on ecological soil functions and possibly the resilience of the investigated ecosystem, as they are likely to occur as a result of future policy decisions. For example, a policy scenario in which intensified agricultural land use is foreseen might show that ecological functions will still exist, but that the land-use is less sustainable due to reductions in the number of species within a given functional group. *Vice versa*, if maximisation of sustainability is sought after in a scenario, this would mean optimisation of the number of species executing certain tasks (within-functional group species diversity) according to the mathematical formulas, and this would generate critical limits on various land use parameters related to sustainability. Evidently, these examples are still in the future, but we are working on it and the first results are very promising.

If the government decides that objectives for soil biodiversity related to soil functions should be set, scientific answers may take a form as discussed above. Questions to be answered require both policy and scientific efforts in an iterative way, with, among others, the following key activities: a) the (policy) choice of reference situations, b) the systematic biomonitoring and building of a database, in order to collect enough data for habitat-response models, and c) fundamental research on the relation between diversity and functions.

References:

Brussaard, L., Behan-Pelletier, V.M., Bignell, D.E., Brown, V.K., Didden, W., Folgarait, P., Fragoso, C., Freckman, D.W., Gupta, V.V.S.R., Hattori, T., Hawksworth, D.L., Klopatek, C., Lavelle, P., Malloch, D.W., Rusek, J., Söderström, B., Tiedje, J.M., Virginia, R.A. (1997) Biodiversity and ecosystem functioning in soil. *Ambio* 26, 563-570

De Ruiter, P.C., Moore, J.C., Zwart, K.B., Bouwman, L.A., Hassink, J., Bloem, J., De Vos, J.A., Marinissen, J.C.Y., Didden, W.A.M., Lebbink, G., Brussaard, L. (1993) Simulation of nitrogen mineralisation in the below-ground food webs of two winter wheat fields. *Journal of Applied Ecology* 30, 95-106

De Ruiter, P.C., A.-M. Neutel, Moore, J.C. (1995) Energetics, patterns of interaction strengths, and stability in real ecosystems. *Science* 269, 1257-1260

European Commission (1998) Understanding Biodiversity, Ecosystems Research Report 25, Directorate-General Science, Research and Development, Luxembourg, office for official publications of the European Communities, EUR 18444

Rutgers, M., Breure, A.M. (1999) Risk assessment, microbial communities, and pollution-induced community tolerance. *Human and Ecological Risk Assessment* 5, 661-670

Schouten, A.J., Brussaard, L., de Ruiter, P.C., Siepel, H., van Straalen, N.M. (1997) Een indicatorsysteem voor life support functies van de bodem in relatie tot biodiversiteit RIVM report 712910005 (55 pages, in Dutch with English summary)

Schouten, A.J., Breure, A.M., Bloem, J., Didden, W., Ruiter, P.C. de, Siepel, H.(1999) Life support functies van de bodem: operationalisering t.b.v. het biodiversiteitsbeleid. RIVM report 607601003 (90 pages, in Dutch with English summary)

Schulze, E.-D., Mooney, H.A. (eds) (1994) Biodiversity and ecosystem function. Springer Verlag, Berlin

United Nations Conference on Environment and Development (1992) Agenda 21. Rio de Janeiro, June 1992.

Wardle, D.A., Giller, K.E. (1996) The quest for a contemporary ecological dimension to soil biology. *Soil Biology and Biochemistry* 28, 1549-1554

World Commission on Environment and Development (WCED) (1987) Our Common Future. Oxford University Press, New York.

Legends of the Figures:

Figure 1
Relation between biodiversity of soil nematodes and management intensity on dairy farms in The Netherlands. The management intensity is given in cattle units, the amount af cattle excreting 41 kg nitrogen per year

Figure 2
Amoeba presentation of indicator values, relative to these in the (chosen) reference (for explanations see table 1 and text)

Figure 3
The habitat-response curves that were obtained for the probability of occurrence of nematode genera in relation to pH in soils in The Netherlands, given that all other abiotic conditions are fixed on their average value in the database.

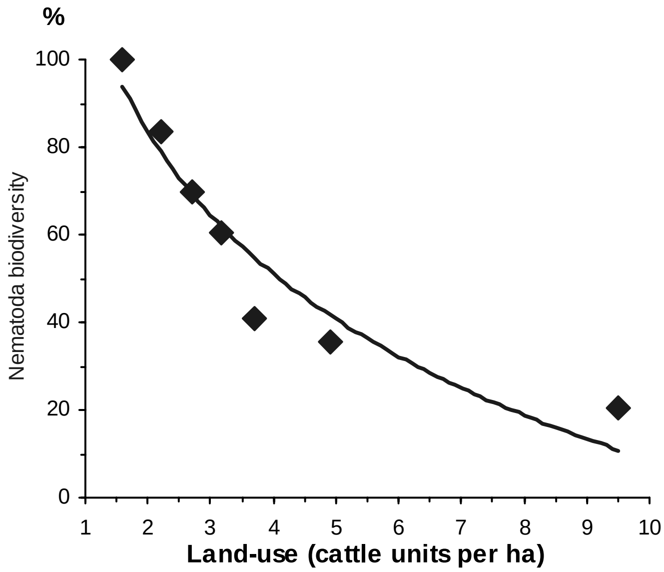
Figure 4
Potential nematode biodiversity map of The Netherlands. The number of nematode genera was predicted for each grid cell of 1 x 1 km using assessed soil characteristics in a Geographic Information System.

Table 1
Biological indicator system for life support functions of the soil. DivS/FG= number of species per functional group, DivF= diversity of functions, MI= maturity index, PPI= plant parasite index. Functional (ecological) groups derived from subdivisions of taxonomic units indicated under Indicatory variables.

Life support functions	***Processes***	***Indicatory variable (taxonomic group)***	***Indicator***
Decomposition of organic material	Fragmentation	**1**. Earthworms + Enchytraeids **2**. Mites	DivS/FG, DivF, mass, number DivS/FG, DivF
	Transformation of organic substrate	**3**. Bacterial degradation routes **4**. Mushrooms, toadstools **5**. Genetic diversity microflora	DivF (biolog test) DivS/FG, DivF Bacterial DNA-polymorphism
Cycling of nutrients	Nitrogen mineralization	**6**. Trophic interactions = 1 + 2 + 7 + 8 + 9 + 10 (in number and biomass)	Nitrogen production (kg N/ha/y) from food web (model calculation)
	subproces:		
	Microbial activity	**7**. Micro-organisms (bacteria/actinomycetes + micromycetes)	Number, biomass, thymidine-incorporation.
	Predation microflora (bacteria + fungi)	**8**. Protozoans **9**. Nematodes **10**. Springtails 2. Mites	Active/inactive cysts, DivS/FG, DivF, MI DivS/FG, DivF DivS/FG, DivF
	Plant feeding	9. Nematodes (+ 2 +10)	DivS/FG, DivF, PPI
	Predation	2. Mites (+ 9 + 10)	DivS/FG, DivF
Availability of nutrients	N-, P- and H_2O-uptake	4. Mycorrhizal symbionts	DivS/FG, DivF
for plants	Nitrification	**11**. Nitrifying bacteria	Nitrate production out of NH_3
Formation of soil structure	Bioturbation + formation of soil aggregates	1. Earthworms + Enchytraeids	DivS/FG, DivF, biomass, number
Stability soil ecosystem	Trophic interactions	**12**. Structure community = 1 + 2 + 4 + 7 + 8 + 9 + 10 (in number and biomass)	Structure pyramid (model calculation)

Table 2*: Summary of indicator values, measured on 20 agricultural grasslands on marine-clay and 17 horticultural farms. "n" is the number of replicates. Significant differences indicated by: *= p< 0.05, **=p< 0.01, ***= p< 0.001, n.s.= not significant.* From Schouten et al., 1999

Soil biota	**Indicators**	**Grassland on marine-clay (n=20)**	**Horticulture (n=17).**	**statistical difference Grl. – Hort.**
Bacteria	Thymidine assimil. (pmol/g/h)	**179.7**	**108.3**	***
	Leucine assimil. (pmol/g/h)	**847.9**	**392.8**	***
	Bacterial biomass (µg C/g)	**232.4**	**56.4**	***
	CFU (10^7 CFU/g)	**17.1**	**2.6**	***
	Potential. nitrification (mg NO3-N /kg/week)	**93.6**	**74.0**	***
Biolog	LogCFU-50 (activity 50%)	**3.73**	**2.87**	***
	H- coefficient (evenness)	**0.39**	**0.6**	***
	gg50 (µg soil with 50% funct.)	**95**	**44**	*
Nematodes	Abundance (num./100 g)	**4629**	**2069**	***
	Number of taxa	**26.1**	**21.8**	*
	Maturity Index	**1.77**	**1.47**	***
	Trophic diversity index	**2.12**	**1.51**	***
	Num. spec. bacterial feeding	**11.4**	**13.3**	*
	Num. spec. carnivores	**0.4**	**0.6**	n.s
	Num. spec. hyphal feeding	**2.1**	**2.1**	n.s
	Num. spec. omnivores	**1**	**1.2**	n.s
	Num. spec. plant feeding	**11.4**	**4.5**	***
	Num. functional groups	**3.9**	**4.3**	n.s
Enchytraeidae	Abundance (num/m^2)	**24908**	**16096**	**
	Number of taxa	**8.2**	**5.5**	***
	Biomass (g/m^2)	**5.6**	**1.10**	***
	Number of *Friderica* (/m^2)	**8654**	**1300**	***
Earthworms	Abundance (num./m^2)	**317.9**	**40.2**	***
	Biomass (g/m^2)	**70.1**	**3.8**	***
	Endogé-species	**2.1**	**0.82**	***
	Epigé-species	**1.2**	**0.06**	***
		(n=1)	(n=1)	
Mites	Abundance (num./m^2)	**37900**	**18100**	
	Number of species	**23**	**20**	
	Number of functional groups	**8**	**10**	
Food web (model-calculations)	N-mineralization (kg N/ha/y)	**335**	**115**	
	C-mineralisation (kg C/ha/y)	**6150**	**1750**	
	Stability	**0.47**	**0.61**	


%
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Nematoda biodiversity
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10
Land-use (cattle units per ha)

Figure 1

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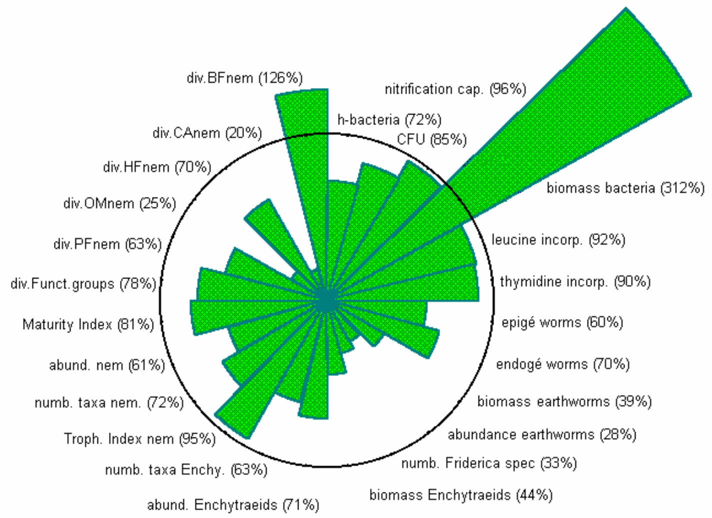
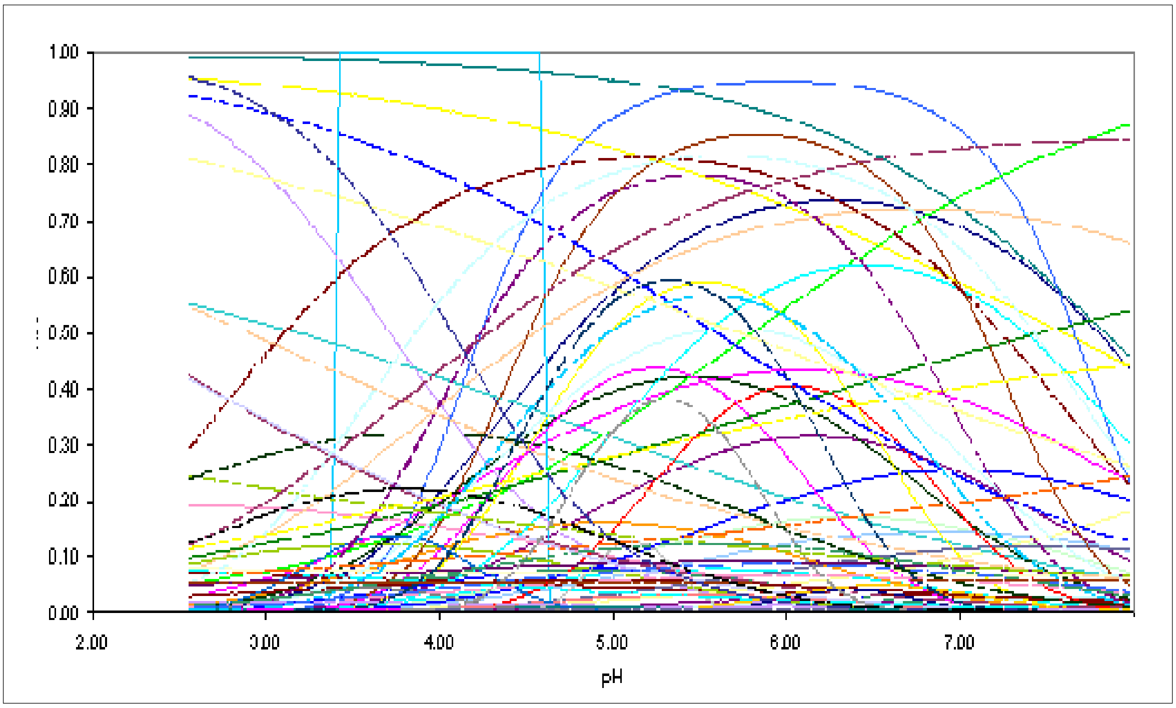

div.BFnem (126%)
nitrification cap. (96%)
h-bacteria (72%)
CFU (85%)
div.CAnem (20%)
div.HFnem (70%)
biomass bacteria (312%)
div.OMnem (25%)
div.PFnem (63%)
leucine incorp. (92%)
div.Funct.groups (78%)
thymidine incorp. (90%)
Maturity Index (81%)
epigé worms (60%)
abund. nem (61%)
endogé worms (70%)
numb. taxa nem. (72%)
biomass earthworms (39%)
abundance earthworms (28%)
Troph. Index nem (95%)
numb. Friderica spec (33%)
numb. taxa Enchy. (63%)
biomass Enchytraeids (44%)
abund. Enchytraeids (71%)

Figure 2: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pH

Figure 3

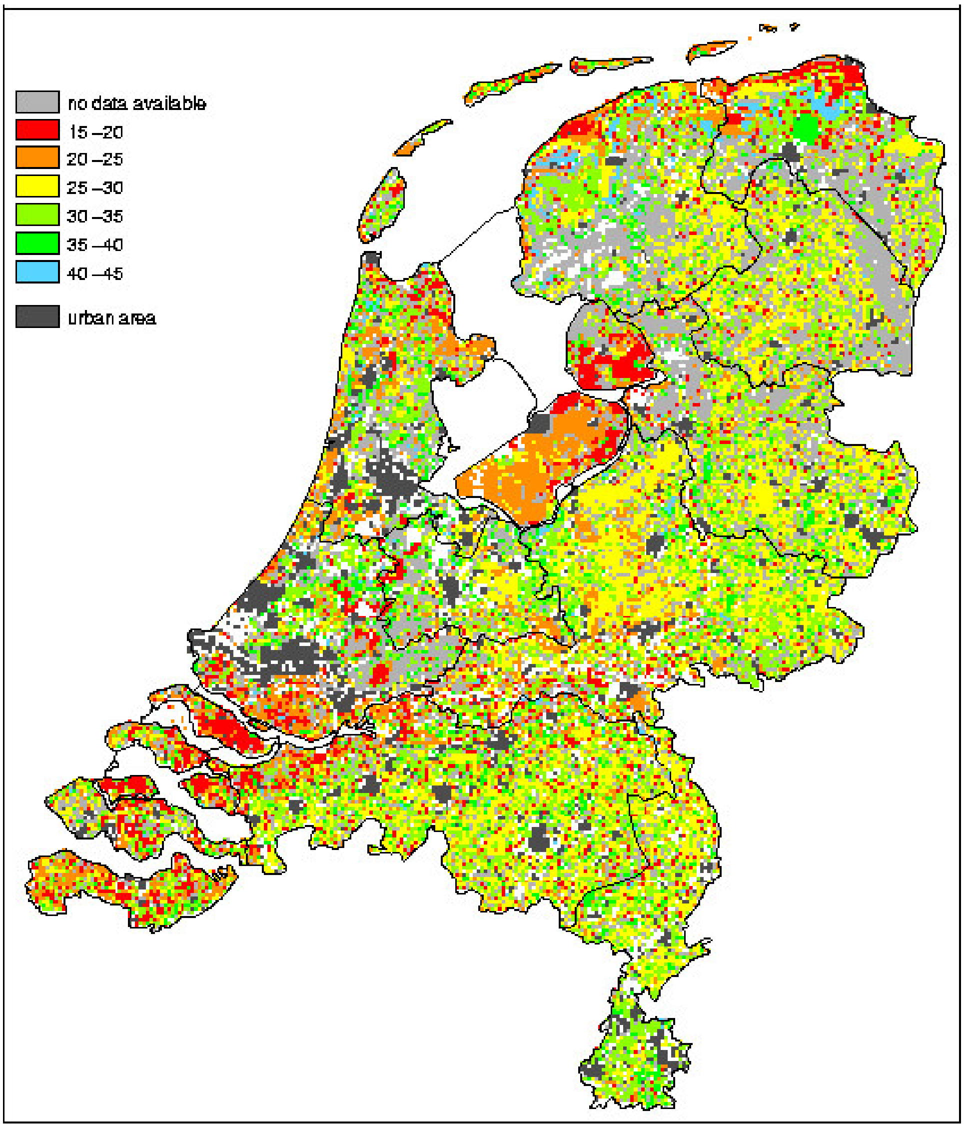

Figure 4