MONITORING SOIL QUALITY IN THE LONG TERM: EXAMPLES FROM THE SWISS NATIONAL SOIL MONITORING NETWORK

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1 Introduction

The proposed Swiss indicator set to assess and monitor the sustainability of agro-ecosystems comprises in total 24 indicators of the topics nitrogen, phosphorus, energy and climate, water, soil and biodiversity and landscape (FAL 2003). The indicator approach aims to assess the success of environmental sound measures in agro-ecosystems. Thus, temporal changes of indicators refer to a specific spatial level, e.g. field, farm, region or national level, and are supposed to give evidence whether a specific land use is sustainable in the long term. However, detecting temporal changes of indicators in agro-ecosystems requires the assessment of their spatial and temporal variation with an appropriate monitoring scheme. This natural variation of an indicator and the variation caused by errors of the measuring procedure sum up to the background variation (“noise”) of a given system. The noise obscures the temporal changes of the indicators caused by anthropogenic activities (“signal”). Consequently, monitoring indicators of agro-ecosystems deal with the detection of anthropogenic changes in comparison to natural changes and to errors of the measuring procedure, or in other words, with the separation of the signal from the noise (Oliver 1993). Concerning this issue, this paper presents selected results for monitoring soil quality as performed in the Swiss Soil Monitoring Network (NABO). Examples are given for measured temporal changes of soil zinc (Zn) and soil lead (Pb) concentration in soil as well as for temporal changes of soil bulk density and soil microbial biomass of a case study.

2 Material and Methods

2.1 Swiss Soil Monitoring Network (NABO)

The objective of NABO, that started in 1985, is to assess soil quality in the long term and to validate appropriate soil protection measures. The network comprises currently 105 observation sites across Switzerland and was stratified according to geology, soil type, land use and regional characteristics. The majority of the sites is used as arable land (34), permanent grassland and rural land (30) and forest (28). Some sites are used for producing vegetables (4), vine (4) or fruits (3). Four replicate bulked soil samples from the soil layer 0-20 cm are taken at the observation sites (10m x 10m) every 5 years. For each bulked sample 25 single cores are taken at the site according to a stratified random sampling scheme. Soil samples are analysed for nine inorganic pollutants (2 M HNO_3-extractable concentrations). To assure the reliability and accuracy of the measurements the quality of sampling, sampling preparation, chemical extraction, analysis and sample storage is assessed (Desaules & Dahinden, 2000; Kurfürst et al. 2004). Temporal chemical changes are calculated as the difference between the mean concentrations of the four bulked soil samples from the first sampling campaign (stored in the archive) and of the soil samples from the subsequent samplings measured in one batch in the laboratory. In addition, at 48 agricultural monitoring sites the management data are recorded annually to assess the input and output fluxes of the heavy metals. This was done so far for the periods 1985-1990 (Desaules & Studer, 1993) and 1995-2001 (Keller et al., 2005).

2.2 Case study for soil physical and biological parameters

In order to extend the monitoring program for physical and biological parameters field experiments were conducted from 2001 to 2003 to test different methods and parameters for soil monitoring. At two arable sites the precision of the method, the sampling precision and the temporal variation of bulk density, porosity, air permeability and penetration resistance was investigated. Further details of the experimental design and methods used are described in Schwab et al. (2005). In this paper we present results for the parameter bulk density that was measured with two cylinders sizes (100 cm^3 and 250 cm^3) at two arable sites at 10 cm and 35 cm soil depth. For each sampling 8 to 10 single cylinders were taken. Soil biological parameters were studied at three grassland and three arable soils in the same years. Each year four bulk soil samples were taken using the same sampling procedure as at the network sites. Samples were analysed for microbial biomass (substrate induced respiration method, SIR, and fumigation extraction, FE), for soil respiration and N-mineralisation (N-min) according to standard methods (FAL 1998).

2.3 Detecting noise and signal

Besides the changes in soil quality caused by anthropogenic activities ("signal") we distinguish (i) procedure errors and (ii) soil dynamic processes that cause the natural background variation ("noise"). Procedure errors comprise changes resulting from all kind of possible errors associated with soil sampling, physical soil preparation, chemical analysis and soil storage. Soil dynamic changes result from soil cultivation, soil biological activity, solute and particle transport, preferential flow, erosion and other processes that are yet unknown. Both sources of the background variation may cause random as well as systematic errors. So far, some of the procedure errors are quantified for some sites, while the variation resulting from soil dynamic processes are hardly known yet (Desaules et al. 2004). In the following the term "method precision" refers to the variation resulting from repeated measures of the same soil sample, the term "sampling precision" indicates the variation of the measurement of the four bulked soil samples per site taken at the same time. The sampling precision may be influenced by procedure errors and soil dynamic processes.

3 Results and Discussion

3.1 Soil chemical changes

Figure 1 shows the temporal changes of the soil Zn concentration for the monitoring sites measured by repeated sampling after 5 and 10 years within the time period 1985-1999. Negative values in Figure 1 indicate a decrease in soil concentration. For the majority of the monitoring sites the soil Zn concentration changed during one decade between –4.1 and 4.6 mg/kg (10% and 90% percentiles) and were approximately normal distributed if pooled for all sites. These changes correspond to about ±3 % of the Swiss guide value of 150 mg/kg for Zn. Some sites showed large increases up to 18.1 mg/kg (arable site) and decreases up to –39.9 mg/kg (vineyard) of the Zn concentration in the topsoil. In the latter case the decrease is meaningless for soil monitoring as the owner exchanged the vine and the top soil at the site, i.e. the site will be abandoned for the monitoring network.

With regard to the land use of the sites soil Zn changes tend to increase at grassland soils and at soils used for special crops. The pattern for the soil Pb changes after one decade was more variable, i.e. for quite a number of sites differences were larger than 10% of the Swiss guide value (50 mg/kg). In particular, at coniferous forest and some grassland sites soil Pb changes larger than 10 mg/kg were found, while most of the soil Pb changes ranged between –1.8 and 4.9 mg/kg (10% and 90% percentiles) corresponding to 4-10% of the Swiss guide value.

In contrast to the soil Zn changes the differences for the Pb values pooled for all monitoring sites were approximately lognormal distributed suggesting that additional processes cause larger deviations for Pb. It is not possible yet to relate changes in soil concentration clearly and quantitatively to individual causes at each site. In particular, the measured changes of Cd, Cu, Zn and Pb at 48 agricultural soils could be explained only to some degree with surface balances for those sites. This discrepancy between measured and predicted soil chemical changes propose that apart from anthropogenic effects also systematic errors resulting from soil dynamic processes and sampling procedure are of major importance for monitoring soil quality in the long term. Hence, the surface balance approach is insufficient and has to be extended to a soil balance approach accounting for soil processes (Keller et al. 2005)

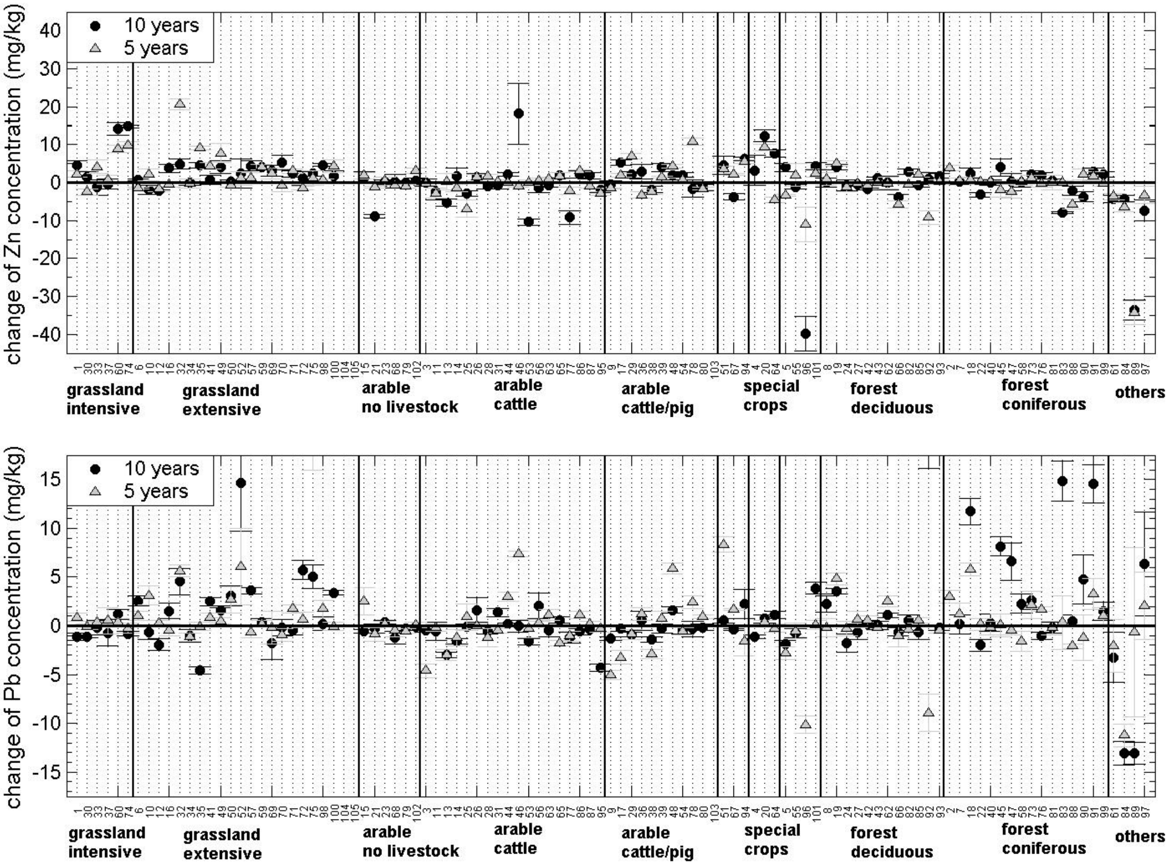

Figure 1: Temporal changes of soil zinc (above) and soil lead (below) concentration at the monitoring sites (102 sites sorted by land use, soil depth: 0-20 cm). The error bars refer to the standard error of four bulked soil samples per repeated sampling.

The standard error of the calculated differences in Figure 1 refer to the sampling precision of the sites. The sampling precision is element as well as site specific. With regard to element the average sampling precision of all sites increased in the order Zn, Ni, Cr (1-2%) < Co, Cu, Pb (3-4%) < Hg, Cd (4-5%), with regard to land use in the order arable < grassland < forest. At some sites, in particular at forest soils and for Hg and Pb, the concentration of the four bulked soil samples showed large variations and were sometimes even not reproducible.

Figure 2 illustrates the role of the sampling precision combined with the natural background variation considering the example for monitoring soil Zn concentration. Both sources of variation determine the detection level of change of the monitoring design. In Figure 2 this level is defined as the prediction interval of a linear regression approach. This interval may be used as criteria to distinguish between signal and noise, i.e. between meaningful measured changes outside the interval and changes within that are of no relevance.

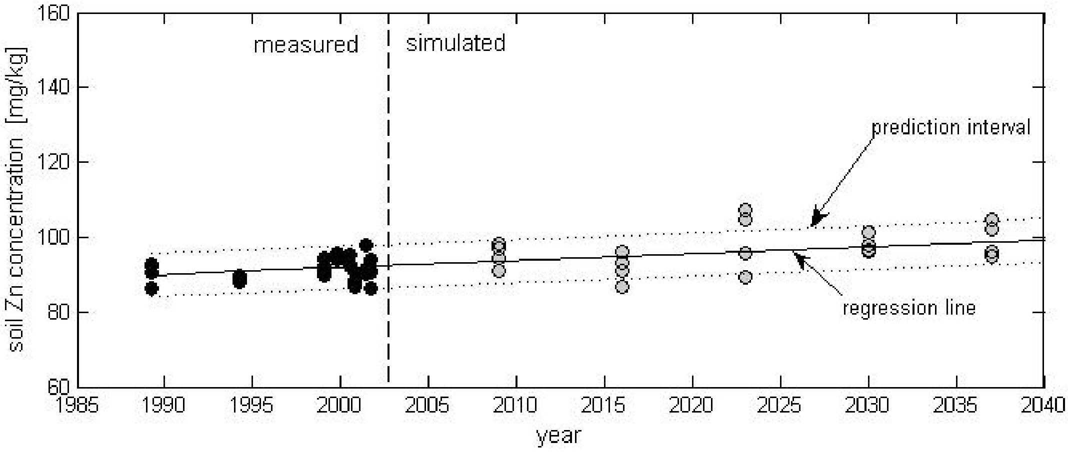

Figure 2: Measured short-term variation of soil Zn concentration (0-20 cm) at a permanent grassland site and the corresponding 95%-prediction interval to distinguish between noise and signal. Simulated Zn concentrations were generated assuming the same linear trend and background variation as measured.

The better the monitoring set up captures both sources of variation the better the detection level can be quantified. In general, changes can be detected earlier if the sampling precision is high and the background variation small. However, from a statistical point of view a sufficient number of repeated samplings within a short time period is required to estimate the background variation, which is time and cost consuming. At the grassland site in Figure 2 and at five other network sites this was done six times within three years (1999-2001). The results of this experimental study suggest that the background variation is also site and element specific (Desaules et al. 2004). Thus, in principle the detection level has to be quantified for each monitoring site and element separately. Because such an approach is not feasible, further research is needed to find relationships between sampling precision and background variation at one hand and site properties such as land use or soil properties at the other hand.

3.2 Soil physical changes

The coefficient of variation (CV) of bulk density was in general larger for the small than for the big cylinders (Figure 3). This may be explained by random effects that had a larger influence on the small than on the big cylinders because the representative soil volumes for the sampled soil structures were clearly bigger than 100 cm^3. The variation of the method was larger for the top soil (10 cm) than for the deeper soil layer (35 cm). In summary, the sampling precision of the soil bulk density was quite high and ranged between 2 % and 6 % for the two fields.

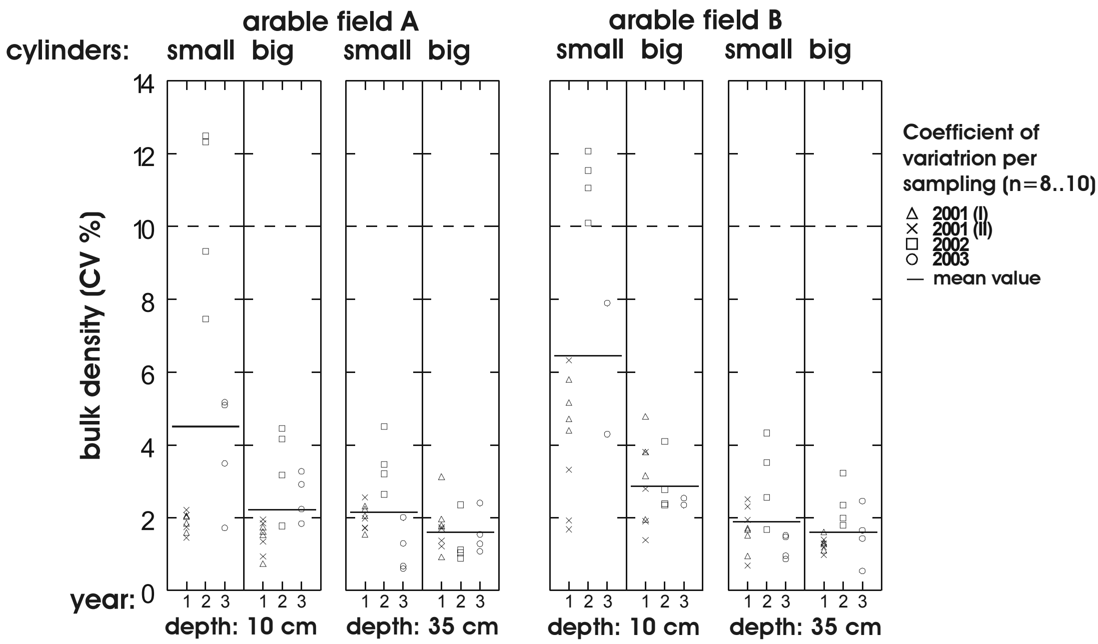

Figure 3: Sampling precision of bulk density for two arable fields and two soil depths, measured in 2001 (1), 2002 (2) and 2003 (3) with small cylinders (100 cm^3) and big cylinders (250 cm^3).

The temporal change of bulk density measured with both cylinder sizes and at both soil depths were in the same range during the three year period. For the two arable fields values between 1.3 and 1.6 g/cm^3 were found. In relation to the mean value for all years bulk density varied between 1 % and 8 % at the individual sites. Apart from anthropogenic effects, the natural temporal variation of bulk density resulted from different site conditions at the samplings, e.g. with regard to soil moisture and temperature.

3.3 Soil biological changes

Figure 4 shows the method precision of the biological parameters measured with fresh and frozen samples during the three year sampling period. Except for N-mineralisation we could achieve in most samples a method precision smaller than 10% CV and a mean method precision smaller than 5 % CV. For some frozen soil samples soil respiration and N-mineralisation were hardly reproducible, suggesting larger variation or a higher risk for extreme values of these biological parameters if frozen soil samples are stored and used as reference soils for subsequent repeated measurements.

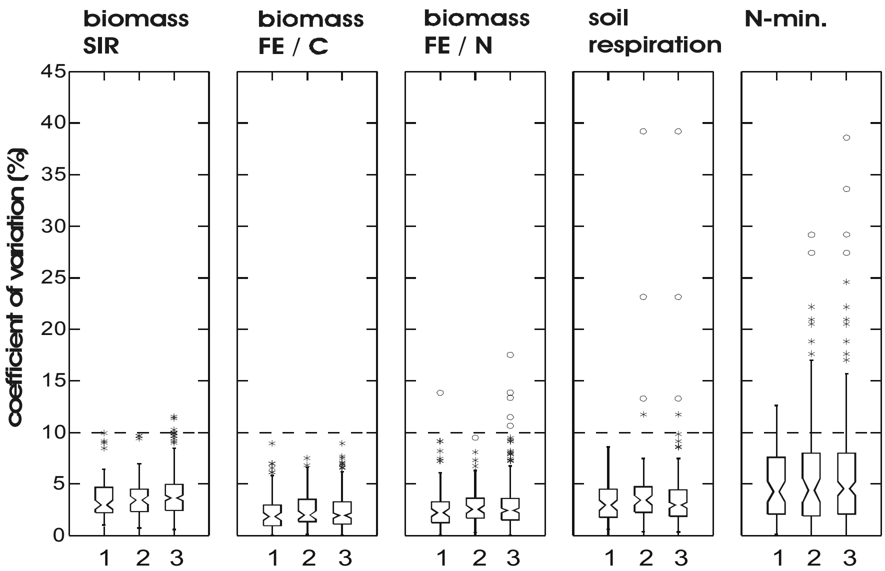

Figure 4: Method precision of microbial biomass, soil respiration and N-mineralisation for fresh soil samples (1), frozen soil samples (2) and pooled for both (3). The values were determined from 4 replicate bulked samples taken at 6 sites for three years (n=72). (* = extreme values, ° = outliers)

Temporal changes of the biological parameters during 2001to 2003 are either due to changes of the stability of the reference samples and method precision or due to possible real changes between the years. At the three grassland sites the microbial biomass in the topsoil was in average 487, 1412 and 816 mg BM-C/kg DM (SIR) for the years 2001 to 2003, while on the three arable sites the average values were 289, 254 and 325 BM-C/kg DM (SIR). Related to the mean biomass of the sites the temporal changes within three years were between 1% and 10% at the grassland sites and between 2% and 21% at the arable sites.

4 Conclusions

The detection level of change we can achieve for a soil indicator and a given monitoring scheme depends on the background variation of the soil system. This noise has to be quantified by an appropriate sampling design and quality assessment in order to separate it from the signal. The detection level can be defined as a prediction interval that takes into account the background variation, i.e. the procedure errors and the natural temporal variation of the indicator. As illustrated for soil chemical changes measured in the Swiss Soil Monitoring Network only temporal changes larger than this detection level, i.e. outside the prediction interval, are then regarded as real anthropogenic changes. The better the monitoring set up captures the background variation, the better the detection level can be quantified. Because our results suggests that the background variation for soil chemical changes is site and element specific, further research should focus on finding relationships between site properties and soil processes that are responsible for the magnitude of the background variation. The evaluation of the method and sampling precision of soil biological and physical parameters were promising concerning the implementation of some of them for soil monitoring in the long term.

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