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Influence of soil water status on collected soil samples

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Abstract

For soil monitoring programmes, the sampling procedure is an essential step. On the one hand, introduced artefacts cannot (or only insufficiently) be corrected a posteriori; on the other hand, sampling artefacts exceed errors introduced by laboratory analyses in most cases. Therefore, it is crucial to know the strengths and weaknesses of the applied sampling technique. The Swiss Soil Monitoring Network NABO collects composite samples from a fixed sampling depth of 0–20 cm (measured from the soil surface). Experience has shown that swell and shrinkage of soil horizons as a result of soil moisture changes are affecting the composition of the collected samples. The bulk density of the fine earth as well as any soil parameter showing a gradient with respect to soil depth is affected. The present article gives an insight into this issue by an illustrative example and by data on water content, bulk density, and organic carbon content measured repeatedly at monitoring sites. Based on these results, we recommend (i) carrying out repeated samplings under similar soil conditions, (ii) recording water content and bulk density of the fine earth for every sampling, and (iii) excluding or correcting results derived from soil samples collected under deviating soil conditions.

Key words: soil monitoring, soil sampling, bulk density, fixed sampling depth

Résumé

L’échantillonnage est une étape d’une importance essentielle pour les programmes de monitoring des sols. D’une part, les éventuels défauts ne peuvent pas être corrigés a posteriori ou seulement avec difficulté, d’autre part, les erreurs d’échantillonnage sont souvent plus lourdes sur le plan quantitatif que les erreurs survenues pendant les analyses de laboratoire. C’est pourquoi il est indispensable de connaître les forces et les faiblesses de la méthode d’échantillonnage choisie. En Suisse, l’Observatoire national des sols prélève des échantillons composites à une profondeur fixe de 0–20 cm (mesurée à partir de la surface du sol). L’expérience a montré que le gonflement et le rétrécissement des horizons du sol sous l’effet de l’humidité fluctuante du sol affectaient la composition des échantillons. Ceci se répercute sur la densité apparente de la terre fine ainsi que sur toutes les propriétés du sol ayant un gradient de profondeur. Le présent article illustre ces interactions par un exemple et les explique à l’aide de mesures répétées de la teneur en eau, de la densité apparente et de la teneur en carbone sur les sites de monitoring. Sur la base de ces résultats, nous recommandons (i) d’effectuer les échantillonnages dans des conditions de sols si possible similaires, (ii) d’enregistrer la teneur en eau et la densité apparente de la terre fine pour chaque échantillonnage et (iii) d’exclure ou de corriger les résultats provenant d’échantillons prélevés dans des conditions de sol différentes.

Termes clés: monitoring des sols, prélèvement d‘échantillons, densité apparente, profondeur d’échantillonnage fixe

Zusammenfassung

Der Arbeitsschritt der Probenahme hat essenzielle Bedeutung für Bodenmonitoringprogramme. Einerseits können allfällige Verfälschungen später nicht oder nur schwer korrigiert werden, andererseits fallen sie quantitativ oft stärker ins Gewicht als Fehler durch die Laboranalytik. Daher ist es unerlässlich, die Stärken und Schwächen der gewählten Beprobungsmethodik zu kennen. Die Nationale Bodenbeobachtung der Schweiz entnimmt Mischproben aus einer fixen Beprobungstiefe von 0–20 cm (gemessen von der Bodenoberfläche). Die Erfahrung zeigte, dass die Zusammensetzung dieser Proben durch das Quellen und Schrumpfen der Bodenhorizonte aufgrund von Schwankungen der Bodenfeuchtigkeit beeinflusst wird. Dies wirkt sich auf das Raumgewicht der Feinerde sowie auf sämtliche Bodeneigenschaften aus, die Tiefengradienten aufweisen. Im vorliegenden Bericht werden diese Zusammenhänge anhand eines illustrativen Beispiels sowie anhand wiederholter Messungen des Wassergehalts, des Raumgewichts und des Kohlenstoffgehalts an Monitoringstandorten erläutert. Aufgrund der Ergebnisse empfehlen wir (i) die Durchführung der Beprobung unter stets möglichst ähnlichen Bodenbedingungen, (ii) die Erfassung des Wassergehalts und des Raumgewichts der Feinerde für jede Beprobung und (iii) den Ausschluss oder die Korrektur der entsprechenden Resultate, falls Artefakte durch abweichende Bodenbedingungen festgestellt werden.

Schlüsselbegriffe: Bodenmonitoring, Probenahme, Raumgewicht, fixe Beprobungstiefe

1 Introduction

The Swiss Soil Monitoring Network (abbreviated NABO for its German name “Nationale Bodenbeobachtung”) was installed in the 1980s (Desaules & Studer 1993). Its main goals are the assessment of soil contamination focussing on background soils (meaning: uncontaminated sites) as well as the early detection of potentially adverse effects. For this purpose, about 100 long-term monitoring sites throughout Switzerland are re-sampled every five years. In addition, management data from more than 40 agriculturally exploited monitoring sites are obtained from the farmers. This allows for a dual approach combining results derived from soil samples (direct monitoring) with mass balances and process models based on management data (indirect monitoring; Keller & Desaules 2004; Della Peruta et al. 2014; Müller & Della Peruta 2014). The latter help to validate and explain temporal evolutions detected by laboratory analyses. Deviating results indicate errors and inadequacies of one or both approaches and require further clarification.
Assessing uncertainties and errors introduced by the used methodology is essential to interpret correctly results produced by direct monitoring, such as temporal evolutions of organic carbon, nutrients, and heavy metal contents. Shifts induced by changes in analytical procedures or unstable laboratory performance must be avoided. These can be reduced largely by the use of adequate control samples and the implementation of standard operation protocols for every step of the whole process chain. Although practitioners and scientists increasingly acknowledge this issue, the impacts of soil sampling and soil status at the sampling date are often neglected. According to our experience, errors introduced by these factors exceed those introduced by laboratory bias in most cases (Desaules et al. 2004). Besides, laboratory errors can very often be corrected by re-analysing archived soil samples, whereas it is impossible to replicate past soil samplings.

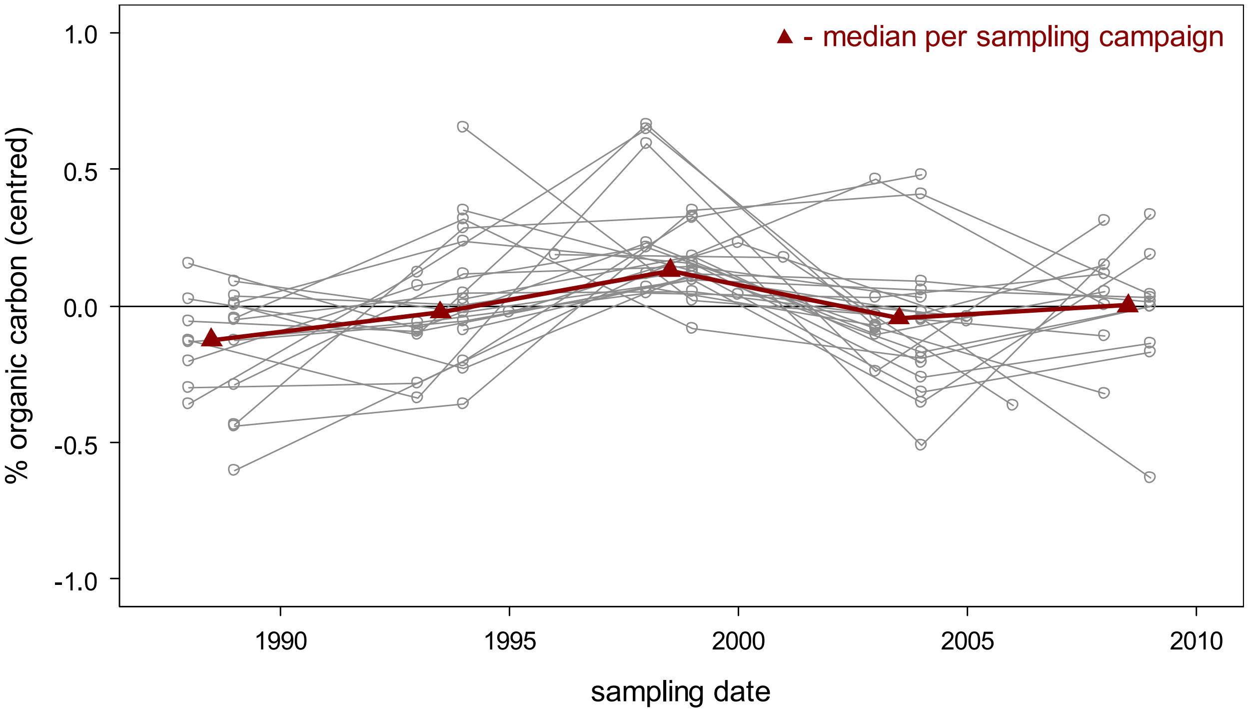

Figure 1: Organic carbon contents (centred with respect to the site’s mean) of soil samples from 18 permanent grassland sites of the Swiss Soil Monitoring Network NABO. Modified from Gubler et al. (2015).

Whereas errors due to the sampling technique itself are minimised by the correct application of standard operation protocols, soil status at the time of sampling remains a substantial source of errors. Soil status mainly refers to soil water content because soils swell and shrink as a result of changes in soil moisture. These issues have been known for at least 20 years (Ellert & Bettany 1995 and subsequent works); nonetheless, soil monitoring programmes did not implement precautions to our knowledge. For some past soil samplings by NABO, artefacts are presumed for various soil parameters including the contents of organic carbon (OC) and several heavy metals. For example, most monitoring sites in permanent grassland show inexplicably high OC content for the third sampling campaign (figure 1). The observed peak seems implausible considering the whole temporal evolutions, hence it was assumed to be an artefact. Indeed, most sites were sampled earlier in the year for the third sampling campaign compared with the remaining ones. Unfortunately, soil water status was not recorded at that time by NABO and the suspected reason for the artefact cannot be proven.

The objective of this study is to assess the key factors influencing soil sampling. The present article provides insights into the effects of soil water status at the time of sampling on the characteristics of the resulting soil samples – on the one hand by an illustrative example, on the other hand by data collected repeatedly at long-term monitoring sites. Finally, recommendations are given to reduce the uncertainties induced by soil status of collected samples within monitoring programmes.

2 Methods

2.1 Sites & samples

NABO runs about 100 long-term monitoring sites covering all relevant land uses. The three major groups are cropland, permanent grassland, and forest. In addition, a small number of sites represent vineyards, orchards, vegetable gardening, urban parks, and conservation areas. Sites are re-sampled every five years for analyses of soil chemical parameters such as contents of OC and heavy metals and pH value. The first sampling campaign was conducted from 1985 to 1989; the sixth sampling campaign was completed in 2014. Selected sites are visited yearly to analyse soil biological parameters and/or physical parameters, namely penetration resistance. Soil samples are collected from an area of 10 m by 10 m accurately re-localised by well-documented reference points and buried magnets. At each of the five yearly samplings, the following samples are taken (Gubler et al. 2015):

- Four composite samples from the top 20 cm each consisting of 25 subsamples. From every square meter of the sampling area, one subsample is taken randomly by using a gouge auger made of steel with a diameter of 2.5 cm (figure 2 on the left).
- Four volumetric samples (one per side) by a Humax core sampler of 4.8 cm diameter. These samples are used to determine soil water content (ω) and bulk density of the fine earth (ρ) relevant for the composite samples.
- If soil characteristics allow: four soil cores down to 75–100 cm soil depth. The cores are separated into pedological soil horizons. The use of a core sampler (figure 2 in the middle) produces volumetric samples, so ω and ρ can be derived directly.

The composite samples have been taken since the first sampling campaign, but the two latter have been taken only since the fourth and sixth sampling campaign, respectively. The composite samples as well as the samples representing pedological soil layers are dried for 48 hours at 40 °C. Subsequently, the samples are crushed by a jaw crusher, and the fine earth is separated from coarser components by passage through a 2 mm mesh. In this condition, samples may be stored for future analyses. To determine ω and ρ, (sub-) samples are dried at 105 °C for 48 hours.

Figure 2: Left: subsample 0–20 cm used for composite sample. Middle: extraction of a soil core by a core sampler at a grassland site. Right: soil cores collected in a coniferous forest (site 83). The displayed soil layers correspond to organic layer (top), A horizon, AB horizon, B horizon, and BC horizon (bottom).

2.2 Analyses & data

The presented data originate from samples collected during the regular five-yearly samplings from 2000 through 2014 (Gubler et al. 2015) as well as from samples collected for soil biological parameters in 2012 and 2013 at 30 selected sites (Hug et al. 2014). Hence, two to five observations are available per site. For the fixed sampling depth of 0–20 cm, the presented results are mean values of analyses conducted for four replicate samples. For pedological soil layers, the fine earth of the four cores was merged, and the presented results were determined from these composite samples.

Water content ω and bulk density of the fine earth ρ were determined from volumetric samples by recording the field-moist and dry masses of the samples ($m_{field-moist}$ and m_{dry}, respectively). The mass of the fine earth m_f was calculated by subtracting the mass of the coarse fraction m_{coarse}, (fraction not passing a 2 mm mesh) from m_{dry}. The sample volume V is given by the dimensions of the sampling device. Thus, the formulae for ω and ρ are

$$\omega = \frac{m_{water}}{m_f} = \frac{m_{field-moist} - m_{dry}}{m_{dry} - m_{coarse}}$$

$$\rho = \frac{m_f}{V} = \frac{m_{dry} - m_{coarse}}{V}$$

Note that ρ relates to the total volume of the sample (and thus to the volume of the entire soil) and not to the volume of the fine earth.

Soil chemical parameters were determined from composite samples for the fixed sampling depth of 0–20 cm and from soil cores for pedological soil horizons. Organic carbon content was determined either by the Swiss Standard Method (FAL 1996) based on re-titration of potassium dichromate, or by determining total carbon content by means of dry combustion (CN-analyser) and subtraction of inorganic carbon where appropriate. The first method is known to produce lower OC content values compared with the latter due to incomplete digestion of organic carbon. Hence, results of the potassium dichromate method needed to be corrected by conversion factors deduced individually per site based on replicate analyses. For most sites, conversion factors close to 1.15 were derived. Content of inorganic carbon was determined according the Swiss Standard Method (FAL 1996) by digestion with sulphuric acid and volumetric metering of the produced CO_2. The presented lead concentration is based on extraction by 2 molar nitric acid and subsequent determination by ICP-MS or ICP-AES.

3 Results & discussion

3.1 Bulk density and water content for fixed sampling depths

The results of the repeated measures for ρ and ω at monitoring sites are presented in figure 3. Considering the results from all sites, ρ is inversely correlated to $\log \omega$. The relation is roughly linear. In other words: elevated ω at soil sampling coincides with low ρ. The observed correlation is induced by one key factor greatly influencing both parameters: OC content. With increasing OC content, ρ is generally decreasing because organic matter has a lower density compared with mineral soil constituents. At the same time, elevated OC content facilitates the soil's capacity to retain water within its pores. Hence, the observed clustering of cropland, grassland, and forest sites seems logical due to increasing OC levels observed from the first through the last group.
Considering the results separately for each site, negative correlations are observed between ρ and ω for most sites. Interestingly, the observed slopes for ρ versus $\log \omega$ vary considerably from site to site. However, the above-mentioned explanation of the relation ρ vs. ω being a result of varying OC content cannot apply for observations from a single site. Although temporal changes in OC content are possible, they are not sufficient to explain the differences within observations from single sites. Consequently, another possible reason is considered: swell and shrinkage of soil. As a result of absorbing water, soil material swells. Contrarily, it shrinks when drying. The extent of swelling and shrinking varies substantially from site to site as well as between soil layers. It depends mainly on the fractions of clay and organic matter, whereby not only their concentrations but also their characteristics are relevant. Generally, soil layers with high OC content like organic layers found within the first centimetres of forest soils, in particular coniferous, show high potentials of swelling and shrinking.

3.2 Illustrative example

The link between swell and shrinkage of soil layers and its influence on samples collected from a fixed sampling depth is not straightforwardly comprehensible. Therefore, we will use an illustrative example based on a coniferous forest site. The respective soil shows a pronounced layering within its top 30 cm with strong gradients for OC content and ρ (figure 2 on the right, figure 4, and table 1). Whereas the uppermost layer contains almost 20% OC, the two following layers contain only 3.5 and 1.5% OC, respectively. Concentrations like those for OC are related to the soil's dry mass; hence, they remain stable regardless of ω. In contrast, ρ decreases with increasing ω as a result of swelling. Consequently, the uppermost soil layers are thicker in moist condition compared with dry condition as illustrated schematically in figure 4. When taken from a fixed sampling depth measured from the soil surface, the resulting samples capture variable proportions of the different soil layers depending on the soil water content. If the soil is sampled in moist condition, the shares of the organic layer and the A horizon are increased, whereas the share of the AB horizon is diminished. Accordingly, these samples show elevated OC content and decreased ρ. Any soil parameter showing a gradient with respect to depth is affected, as demonstrated in table 1 for lead content.

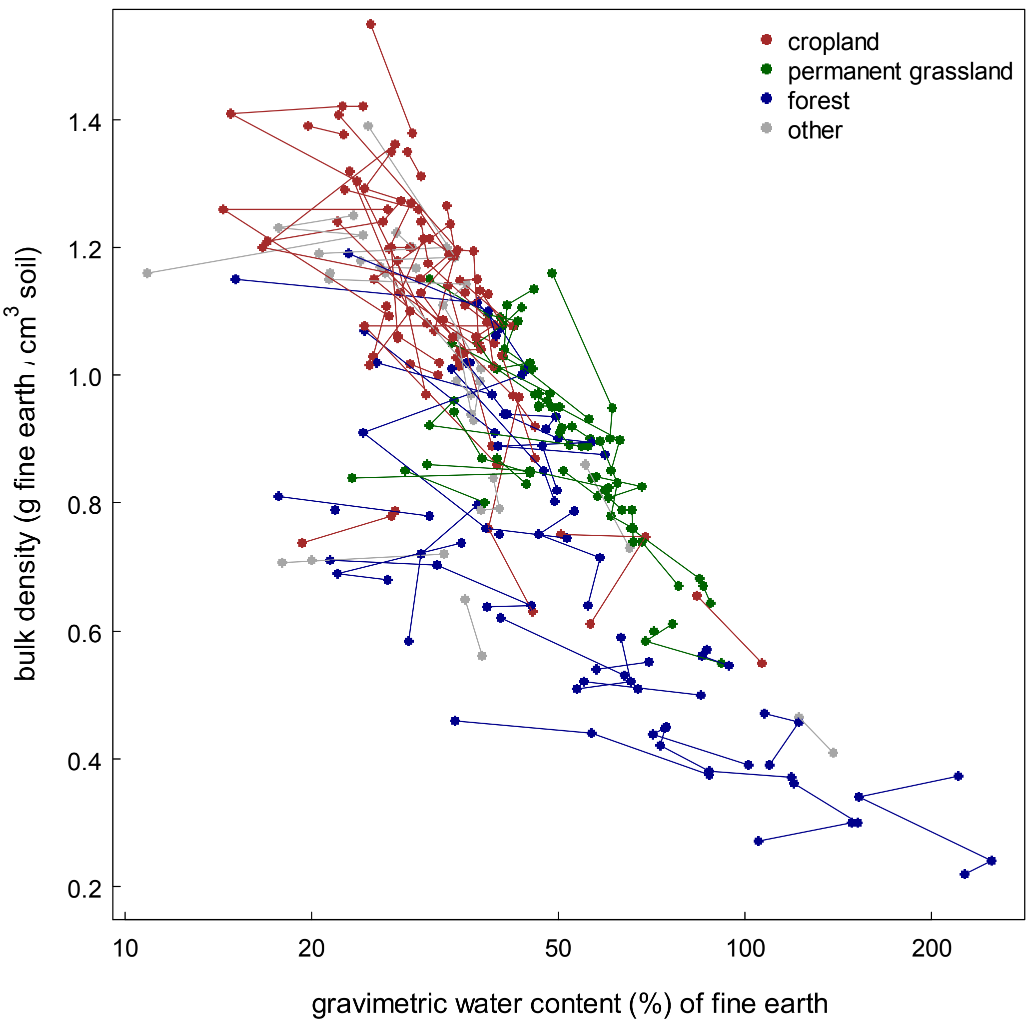

Figure 3: Bulk density ρ vs. gravimetric water content ω determined for soil samples from long-term monitoring sites at different sampling dates. Observations from the same site are connected by lines.

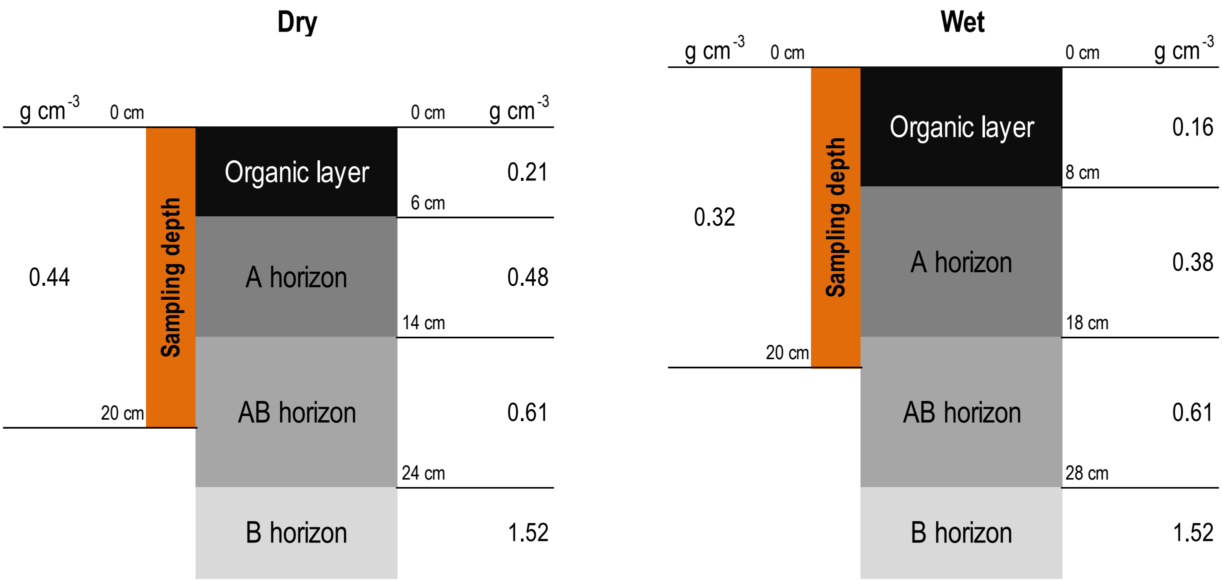

Figure 4: The impact of deviations in soil water content on the composition of samples collected from the top 20 cm at site 83. The provided numbers are soil depth (measured from the surface) and bulk density of fine earth (ρ) per soil horizon and for the sampling depth. Modified from Meuli et al. (2014).

Table 1: Bulk density, organic carbon contents, and lead (Pb) content of the soil layers presented in figure 3 and the top 20 cm samples collected from dry and wet soil at site 83. Modified from Meuli et al. (2014).

Soil layer	Bulk density (g cm^{-3})	Organic carbon (%)	Pb (mg kg^{-1})
Organic layer	0.16 (wet), 0.21 (dry)	19.5	62.4
A horizon	0.38 (wet), 0.48 (dry)	3.5	62.4
AB horizon	0.61	1.5	17.8
B horizon	1.52	0.5	10.0
Dry soil 0–20 cm	0.44	5.0	43.8
Wet soil 0–20 cm	0.32	6.4	53.8

The magnitude of the described effects of soil water status on sample characteristics strongly depends on the soil properties. Whereas effects are very strong at the site used as illustrative example, they are negligible or absent at many other sites. Thus, under which conditions do these effects become important? They are promoted by a pronounced layering in the top soil, especially if some of these layers have elevated OC contents. Such conditions are met by most forest soils and, to a minor degree, soils under permanent grassland. In contrast, most soils under croplands show no or only weak layering and even distributions of OC in their top 20 cm — possibly with the exception of plots that are under no-tillage managements for long periods. Additionally, the relation between ρ and ω is difficult to interpret for cropland soils because their structure is strongly influenced by soil working.

3.3 Interaction of OC and bulk density

The results of the repeated measures for ρ and OC are presented in figure 5. Comparing the results from different sites shows that high OC content coincides with low ρ and vice versa. As already stated above, increased OC content induces decreased ρ due to the lower density of organic matter compared with mineral soil components. Comparing the multiple measurements per site shows that relations between the two parameters are rather inconsistent. For some sites, the observed relations fit the expectations, e.g. for the two sites presented in detail in figure 6. For the forest, increased OC content coincides with decreased ρ, whereas no correlation between the two parameters is observed at the presented cropland site. Presumably, the effects of soil moisture are negligible compared with those caused by soil working on cropland. However, there are sites where increased OC content is observed with increased ρ. In this context, it must be considered that the results for both parameters contain uncertainties. Consequently, the observed relation may be altered by errors, especially if the correlation between OC content and ρ is weak or absent.

3.4 Critical evaluation of fixed sampling depth

The previous section demonstrated how soil water status at the time point of sampling may influence the characteristics of the collected soil samples. Such interferences may distort the results of temporal evolutions provided by monitoring programmes. For example, the peak observed between 1995 and 2000 for OC contents displayed in figure 1 is attributed to higher soil moisture at these samplings. The artefact is induced by the fixed sampling depth measured from the soil surface; hence, the applicability of the sampling method must be questioned. Alternatively, soils can be sampled by taking a separate sample per pedological soil horizon. This approach avoids the problems related to swell and shrinkage of soils but involves other issues, especially the correct separation of soil horizons.

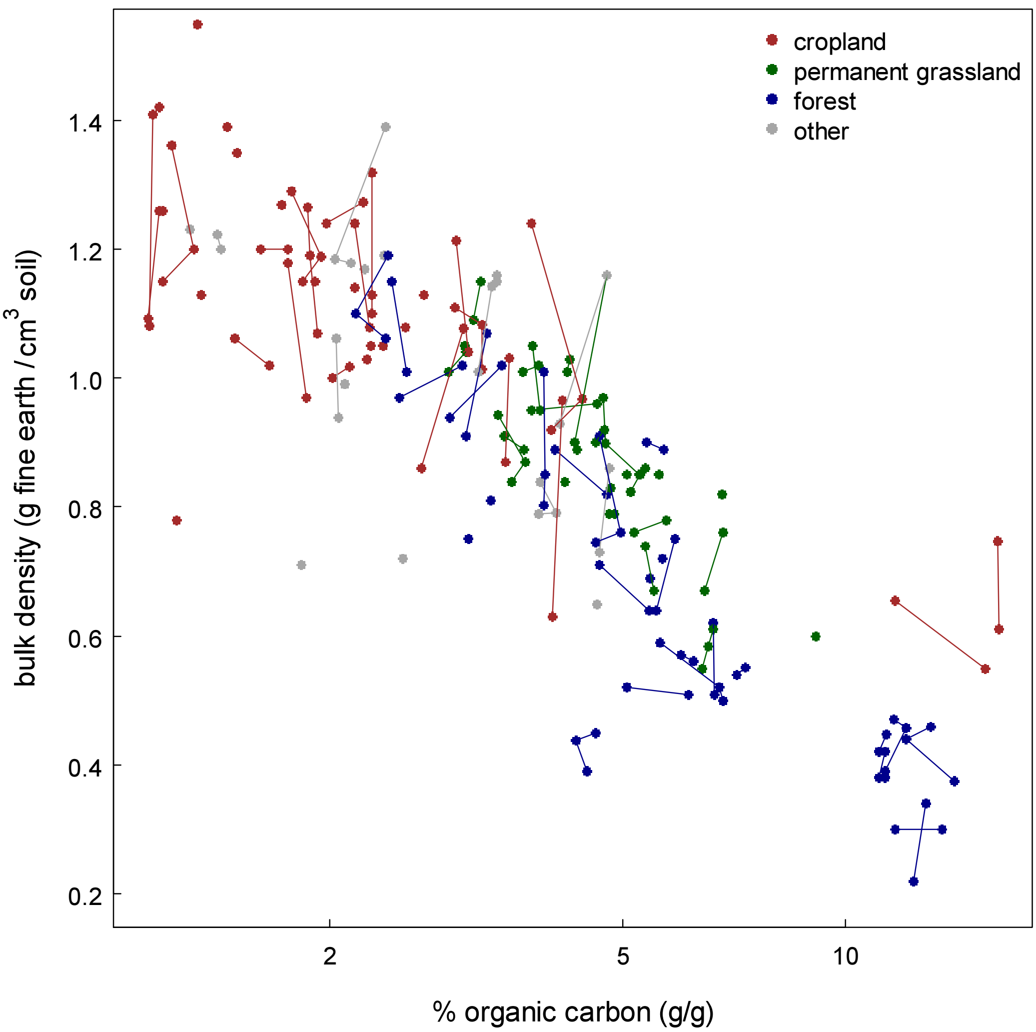

Figure 5: Bulk density ρ vs. organic carbon content determined for soil samples from long-term monitoring sites at different sampling dates. Observations from the same site are connected by lines.

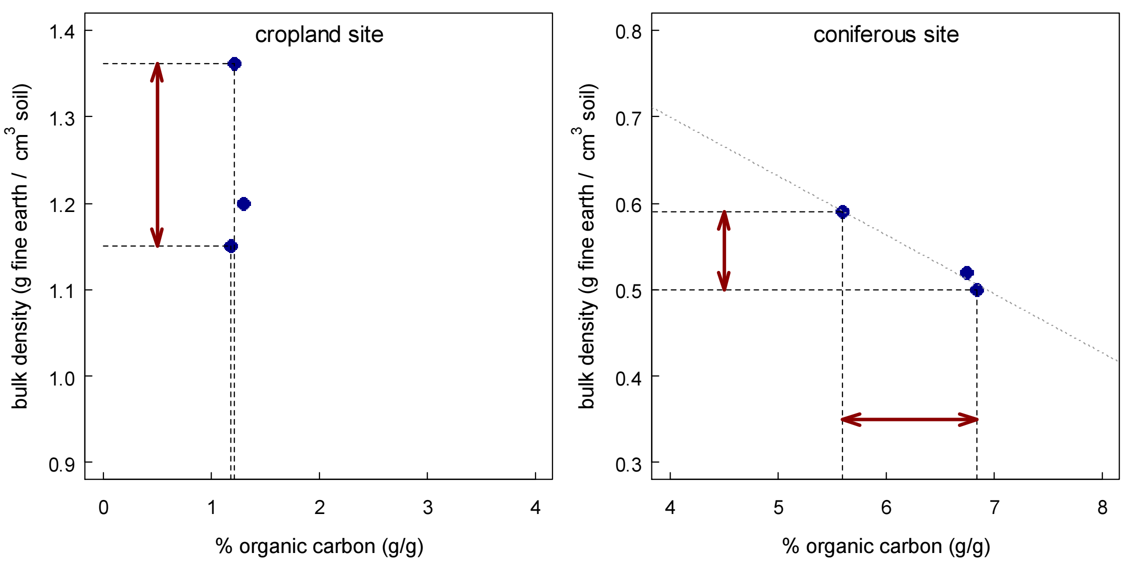

Figure 6: Bulk density ρ vs. organic carbon content of soil samples measured at different dates for two selected sites: cropland site (left) and forest site (right).

The main argument in favour of a fixed sampling depth is its simplicity and robustness. Most people are able to read a distance of 20 cm and to adjust the sampling device accordingly. In contrast, taking soil samples per soil horizon requires thorough pedological knowledge. Furthermore, in many cases, there is no clear boundary between horizons. For stocks calculated for the whole soil profile, these errors cancel out. However, soil monitoring programmes require information on topsoils. Consequently, we still favour using a fixed sampling depth, although certain measures must be implemented to reduce the related uncertainties and to correct induced artefacts. (Besides, the sampling protocol of a long-term monitoring programme cannot be changed fundamentally after 20 years.)
In order to reduce the uncertainties induced by soil water status, two strategies have been pursued by NABO since the fourth sampling campaign starting in 2000: First, artefacts can be reduced by avoiding large differences in soil water status between samplings. Soils should not be sampled when they are extraordinarily wet or dry. When samplings are planned, the time of year of the past samplings at the same site must be considered. Obviously, these demands cannot always be met in a soil monitoring programme. Second, we further implemented a mechanism with which deviating soil conditions at samplings are detectable and correctable. To do so, volumetric samples of the top 20 cm as well as samples from pedological soil horizons (collected from soil cores) are needed. The former provide information on ρ and ω with respect to the sampling depth of 0–20 cm, whereas the latter provide information about soil layering and concentration gradients. Having this information, two options are applicable: On the one hand, it can be controlled whether soil conditions at different sampling dates are comparable by consulting the respective ρ and ω; on the other hand, the results (e.g. OC content) from a sampling date may be recalculated to reflect the soil conditions at another sampling date.
The soil samples collected additionally also offer further benefits: The knowledge of ρ allows relating concentrations not only to mass but also to soil volume, which under certain circumstances may be more appropriate. Furthermore, it allows transforming concentrations into stocks. Finally, temporal changes of gradients help to understand and explain the evolutions observed for the top 20 cm of the soil.

4 Conclusions & recommendations

Every sampling scheme has its strengths and weaknesses. In order to avoid artefacts and misinterpretations, it is crucial to know potential problems of the applied sampling scheme. Using a fixed sampling depth is a simple and robust technique to monitor topsoils because the separation into pedological soil horizons, which requires knowledge and leaves room for interpretation, is avoided. In turn, the characteristics of the collected soil samples are influenced by the soil water status at the sampling date. For most sites, samples tend to have lower ρ and elevated OC content when taken under wet conditions compared with samples taken under dry conditions. In general, all parameters showing gradients with respect to depth are affected. Primarily, such artefacts are most likely observed at forest sites and, to a minor extent, at grassland sites, whereas cropland sites often show no correlation between ρ and further parameters for the top 20 cm of soil.

To guarantee the validity of monitoring results, several measures are recommended:

- Differences in soil water status between sampling dates at the same site should be minimised. In particular, samplings under wet conditions (e.g. exceeding field capacity) should be avoided. We suggest (re-)sampling during the same time of year.
- Soil conditions must be recorded for every sampling, particularly ρ and ω for the sampled soil layer. When composite samples are taken using a device with an ill-defined volume (as the half-core used by NABO), additional samples are needed for that purpose.

- Soil layering and gradients of the properties of interest must be known for every site. Ideally, these parameters are recorded for every sampling date because temporal evolutions of gradients help to understand and interpret the changes observed for the topsoil.
- Finally, results from sampling dates with deviating soil water status should be either discarded from time series, or corrected to reflect soil conditions comparable to the remaining sampling dates.

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6 Indices

6.1 List of figures

6.1 List of tables