ASSESSMENT OF HEAVY METAL LEACHING RATES FROM TOPSOILS ON REGIONAL SCALE (PART I)

J. Schmidt, A. Steinz, M. Schindewolf (Technical University Freiberg, Germany)

ABSTRACT: The leaching rate of heavy metals with drainage water is a significant criterion for assessing heavy metal concentrations of soils and associated risks of ground water pollution. However, the transport rates of heavy metals in soils are difficult to quantify. First of all monitoring is limited to small lysimeter plots and results are hardly transferable. Secondly the solid-liquid-transfer conditions in soils are highly variable, primarily due to the fluctuating retention time of percolating soil water.

This paper aims to introduce a new method that allows to estimate the leaching rate of heavy metals from contaminated top soils for standardised transfer conditions. The method should provide an effective and easy to use tool for the assessment of contaminated soils on regional scale. The developed method is based on metal specific transfer functions which have to be determined experimentally. For laboratory tests 16 undisturbed soil columns were taken at different highly contaminated sites in the German States of Saxony and Baden-Wuerttemberg. Parallel to the column tests the mobilizable metal contents of each of the tested soils were determined using different standardised extraction methods (DIN 38414, 19730, 19735). Measured metal concentrations of percolating soil water at unsaturated, steady-state flow conditions were plotted as a function of corresponding mobilizable metal contents of the tested soils. This comparison results in a set of empirical functions - one for each extraction method respectively metal species. Best fit was obtained using the NH₄NO₃-extraction (DIN 19730), where correlation coefficients range between r=0,62 and r=0,85. Since NH₄NO₃ mobilizable metal contents are available on regional scale in Germany the empirical transfer functions allow to calculate metal concentration of percolating soil water based on mobilizable metal contents as determined by simple extraction methods. As a first example heavy metal concentrations were calculated for the State of Saxony based on available NH₄NO₃ monitoring data of about 4600 topsoil samples. Leaching rates were calculated by multiplying the resulting metal concentrations with local groundwater recharge rates. In order to assess subsurface retention the calculated topsoil losses for Zn and Pb were compared with measured metal discharge rates of a selected river catchment resulting in a much greater retention of Pb than Zn.

INTRODUCTION

On the background of soil and groundwater conservation particular attention has been focused on the leaching of heavy metals from contaminated topsoils for many years. There are various reports referring to laboratory methods (e.g. Davidson et al. 2006), field experiments (e.g. Beesley et al. 2010) and modelling approaches (e.g. Dijkstra et al. 2004) in order to assess the mobility of heavy metals in soils. However, only a few attempts have been made to evaluate the fate of heavy metals in soils on regional scale (e.g. Bontena et al. 2008).

Since total concentrations of heavy metals in soils are poor indicators for the risk of ground water pollution leaching rates are significant criterions for the assessment of contaminated soils. The mobility of heavy metals in soils is usually tested by standardized leaching experiments. Legal regulations in many countries (e.g. BBodSchV 1999) are based on this kind of extraction procedures. Generally accepted are batch tests using a 24 h elution procedure at a liquid/solid ratio of 10 : 1. This kind of experiments represents a worst case (Hirner et al. 1998), which means that each soil particle is circulated by the leaching agent. However, under natural conditions the liquid/solid ratio is usually less than 1 : 1 and soil water percolates most commonly along preferential flow paths (Beven and Germann 1982, Camobrec et
Consequently certain parts of the soil matrix won’t get in contact with percolating water under unsaturated and even under saturated conditions. Accordingly standard batch tests are not capable to estimate natural leaching rates. Instead of that these tests might be an adequate method in order to quantify the pool of mobilizable metals under standardized conditions. Quantifying this pool is helpful in terms of an overall risk assessment but provides no answer regarding actual leaching rates.

Alternatively soil water concentrations (and fluxes) of heavy metals could be measured in the field using lysimeters or suction cups in order to sample the percolating pore water directly (e.g. Tiensing et al. 2001). However, this kind of field based techniques have only a minor potential for risk assessment because the various parameters influencing the leaching processes are highly variable under natural weather conditions. Furthermore field based monitoring is very laborious and thus limited to a few number of small plots. As a consequence results are hardly transferable. This is especially true for the retention time of the percolating soil water, which is one of the most sensitive parameters affecting the solid-liquid transfer. Hence metal concentrations of in situ soil water samples will be highly variable as Fig. 1 shows. In order to assess mean leaching rates long term monitoring is essential.

The aim of the present study is to assess the leaching rates of heavy metals from contaminated top soils on regional scale. The newly developed method is based on metal specific transfer functions which are derived from undisturbed soil column leaching experiments under controlled water transport conditions. The transfer functions allow to calculate metal concentrations in soil water depending on mobilizable metal fractions under standardised transfer conditions. The method should provide an effective and easy to use GIS-tool for the assessment of contaminated soils.

Fig. 1: Temporal variation of zink concentration of in situ water samples taken at Hilbersdorf monitoring station in a depth of 0.4m (Source: Sächsisches Landesamt für Umwelt und Geologie)

**MATERIALS AND METHODS**

**Sampling sites.** For laboratory tests 16 undisturbed soil columns were taken at different highly contaminated sites in the German Federal States of Sachsen and Baden-Wuerttemberg (see Fig. 2). The experimental data selected for presentation in this paper refer to an agricultural site located south of the village Hilbersdorf close to the city of Freiberg/Saxony (50° 55’ N, 13° 21’ E, 425 m above sea level). Besides the high geologic content of heavy metals the pollution of top soils with metals and metalloids at this site results from emissions of local lead and silver mines and smelter plants over more than eight
centuries culminating in the first half of the last century. The mining complex “Muldenhuetten” was the main source for pollution in that area with high levels of zinc, cadmium, arsenic, and lead emissions. In 1991 the Saxonian Environmental Report stated an immision of lead in the Hilbersdorf area of 40mg/(m²*30d). Referring to cadmium an immision of 0.8mg/(m²*30d) was reported. The Saxonian agency for Environment and Geology (Saechsisches Landesamt für Umwelt und Geologie) is using this site as a long-term soil monitoring station. These investigations include the sampling of soil solution in the time period between April and November. The sampling is performed by using ceramic suction cells at a constant vacuum of 200hPa. Some results from these samples are presented in Fig. 1.

![Study areas](image)

**Fig. 2: Study areas**

Experimental results are used for the assessment of heavy metal leaching on regional scale referring to the State of Sachsen (18400 km²) with special respect to the Mulde river basin (7400km²). Topsoils of the Mulde catchment (Cambisols, Luvisols, Stagnosols and Fluvisols) have arisen predominantly from loess deposits except the upper mountain range where weathered rock soils are distributed. Mean yearly precipitation varies between 500mm/a in the northern lowlands up to1200mm/a in the southern mountain range.

Intensive mining activities and metal processing during the last centuries cause severely contaminated topsoils in some parts of the saxonian mountain range. Most important contaminants are Zn, Cu, Pb, Cd, Ni, Cr, Hg, and As.

**Soil sampling.** Undisturbed soil columns (length: 50cm; diameter: 12.5cm) were taken using stainless steel tubes which were pressed carefully into the soil and excavated manually. In order to press the tubes strongly vertical into the soils a specially designed duct was applied. To avoid any damages at the front of the tubes during penetration a removable cutting ring was positioned at the lower end of the tubes. Additionally, bulk soil samples were taken from each site.
Soil properties. The properties of the soils were determined referring to the following parameters: particle size distribution (determination with pipette by KOEHN), soil moisture suction curve, pH of the soil solution, content of organic carbon (burning with oxygen, STROEHLIN Cmat 550). The results are compiled in Table 1. The pH of the soil was determined for CaCl₂ (0,01M), KCl (0,1M) and deionized water as solvents. A 10g sample of air-dried soil has been mixed with 25ml of the solvent at room temperature. The pH was measured twice, once after 4 hours and again after 24 hours.

Table 1: Particle size fractions, organic matter content, bulk density, pH for CaCl₂ (0,01M), KCl (0,1M) and H₂O after 4 hours and after 24 hours

<table>
<thead>
<tr>
<th>sample depth [cm]</th>
<th>Stone M%</th>
<th>fine soil particles (yields 100 M.%)</th>
<th>bulk density [g/cm³]</th>
<th>organic matter content [M%]</th>
<th>pH after 4 hours (21.7 °C)</th>
<th>pH after 24 hours (22.2 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-25</td>
<td>34.0</td>
<td>43.5</td>
<td>14.4</td>
<td>1.18</td>
<td>2.49</td>
<td>4.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.01</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.00</td>
<td>5.08</td>
</tr>
<tr>
<td>25-40</td>
<td>56.3</td>
<td>55.6</td>
<td>35.9</td>
<td>9.0</td>
<td>0.51</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.48</td>
<td>5.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.92</td>
<td>4.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.54</td>
<td></td>
</tr>
</tbody>
</table>

Extraction of heavy metals. Different batch tests (DEV-S4/DIN 38414, DIN 19730) have been used in order to quantify the pool of mobilizable metals under standardized conditions. The DEV-S4/DIN 38414-4 method uses 50g of air-dried soil which is mixed with 500ml deionised water. The mixture is shaken in an over-head-mixer for 24 hours. The extract is obtained by centrifugation at 2500rpm or vacuum filtration (filter pore size 0.45µm). The soil equilibrium extract according to DIN V19735 is obtained using 200g air-dried soil. The sample (<2mm) is mixed with deionised water added drop by drop under constant kneading until field capacity is reached. Avoiding evaporation the sample is kept at 5°C for 24 hours. The extract can be obtained by vacuum filtration (filter pore size 0.45µm). The NH₄NO₃ extraction method as described by DIN 19730 uses 50 ml of 1M NH₄NO₃ solution which is added to 20g of soil material (<2mm). The suspension is shaken in an over-head-mixer for 2 hours. Similar to the above mentioned methods the extract is obtained by centrifugation or filtration. The mass-related extractable concentration [µg/kg] can be calculated by multiplication of the resulting dissolved element concentration with the soil/extraction solution ratio.

Column leaching experiments. The laboratory setup consists of 4 vacuum-controlled workstations comprising the following components:
- stainless steel cylinders coated inside with Teflon (length: 50cm; diameter: 12.5cm) each housing an undisturbed soil column with a porous plate/membrane closures at the bottom
- an electronically controlled rainfall simulator
- two separate sample cells for each soil column; the lower cell is coupled with a balance in order to measure the volume rate of percolating soil water
- an electronically controlled vacuum in order to adjust flow rates and retention times of percolating soil water
- micro-tensiometers and TDR sensors for the measurement of capillary water tension (pressure head) and soil moisture
- a data logging system.
The experimental set-up is similar to the design described by Rambow and Lennartz (1993) which allows to study the leaching of heavy metals in undisturbed soil columns under vadose zone conditions.

**Legend:**

1. Stainless steel cylinders coated inside with Teflon
2. Micro-tensiometers
3. TDR-sensors
4. Rainfall simulator
5. Peristaltic pump
6. Reservoir (1.5l)
7. Water level sensor
8. Porous glass plate
9. Column mounting
10. Filter foil (Nylon, 0.1µm)
11. Bearing plate (Polyester)

**Fig. 3:** Schematic view of the experimental setup (Schmidt & Kaltschmidt 2001)

Soil water tension and volume rate respectively retention time of percolating water could be varied according to natural water flow conditions (Fig.4). Soil water tension, soil water content, applied vacuum, and the amount of precipitation are controlled continuously over the entire experiment which can
last up to several months. By using two separate sample cells for each soil column a constant vacuum at the bottom end of the soil column can be maintained during the sampling of the percolate (for details see Fig. 3). Sample cells are placed on a balance to register the volume rate of percolating water continuously. The experimental setup was placed in an air conditioned room with a constant temperature of 20 °C.

A “synthetic rain water” is used in order to simulate natural rainfall conditions (Table 2). After adjusting the predefined flow rate of percolating soil water by means of the vacuum at the column bottom water samples were taken for unsaturated (pF=1.4) and saturated steady-state flow conditions. Simulated rainfall intensity was set to 1ml/h in case of unsaturated flow respectively 100 ml/h in case of saturated flow. Sampling was continued until heavy metal concentrations in the percolates are constant, which requires up to 3 months of continuous percolation depending on retention time and volume rate of flow (Fig. 4). Water conductivity was used as an indicating sum parameter. The heavy metal concentrations in the percolates have been determined for the following elements: As, Cd, Cr, Cu, Hg, Ni, Pb, Sb and Zn using an ICP-MS analyser. In addition, pH and redox potential are measured.

The soil column tests have been performed according to the following procedure:

1. Drainage of field moisture from the soil columns at a vacuum of 630hPa in order to remove remaining soil water that has not been exchanged since the samples were taken.
2. Watering of the columns from the bottom in order to avoid trapped air in the columns
3. Adjustment of the precipitation rate to 1ml/h (1st step)
4. Optimising of the vacuum for the adjusted precipitation rate up to the establishment of the desired soil moisture tension (pF=1.4) as an average of the three tensiometers in each soil column.
5. The sampling of percolating water starts as soon as the desired soil moisture tension is established within the soil column.

<table>
<thead>
<tr>
<th>Na⁺</th>
<th>K⁺</th>
<th>Mg²⁺</th>
<th>Ca²⁺</th>
<th>Cl⁻</th>
<th>N</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>219.1</td>
<td>121.7</td>
<td>83.1</td>
<td>548.0</td>
<td>459.0</td>
<td>43.6</td>
<td>137.7</td>
</tr>
</tbody>
</table>

Fig. 4: Retention time of percolating soil water as a function of volume rate of flow.
6. Continual sampling until the heavy metal concentrations in the percolates are constant. The conductivity of the percolate is used as a sum parameter. Also, pH and redox potential are measured. Samples were stored at 4 °C until metal concentrations are analysed.

7. The heavy metal concentrations in the percolates has been determined for the following elements: As, Cd, Cr, Cu, Hg, Ni, Pb, Sb and, Zn.

This procedure assures comparable results over all test runs.

RESULTS AND DISCUSSION

Experimental results. As example for all investigated heavy metals Fig. 5 shows the topsoil zinc concentrations for the Hilbersdorf experimental site as obtained by the different extraction methods.

![Fig. 5: Topsoil zinc concentrations for the Hilbersdorf experimental site as obtained by the different extraction methods](image)

The by far highest concentrations are gained using the NH4NO3 extraction method because ammonium nitrate is a much more aggressive extraction agent than water. The difference in concentration amounts to more than one order of magnitude compared to the water based methods. The equilibrium extract yields somewhat higher concentrations because of the closer liquid/solid ratio.

Zinc concentrations determined in the percolates of the column tests vary over time until initial soil water is entirely substituted by continuous supplied rainwater. Theoretically concentrations should reach an approximately constant value when the ratio of the volume of percolated water and the watered pore volume is greater than 1. Actually concentrations approach the constant level at a ration of 1.2 as Fig. 6 shows. Precautionally only concentrations measured for rations >1.5 are taken into account for further analyses.

In Fig. 7 zinc concentrations in the percolates of undisturbed soil columns are compared to in-situ pore water samples with respect to water content (unsaturated versus saturated) and volume rate of flow (respectively rainfall intensity). Taking the mean in-situ pore water concentration as reference the best correlation can be determined for the unsaturated column tests at a rainfall intensity of 1ml/h which equals 713 mm/a. Therefore only the unsaturated test variant is evaluated for further analysis.
In Fig. 8 measured zinc concentrations of percolating soil water at unsaturated, steady-state flow conditions were plotted as a function of corresponding mobilizable metal contents. This comparison results in a set of curves respectively empirical functions - one for each extraction method. Taking account of all investigated metal species the respective functions are compiled in Table 3. This set of transfer functions allow to calculate metal concentrations of percolating soil water based on mobilizable metal contents as determined by simple extraction methods. Best fit was obtained using the NH$_4$NO$_3$-extraction (DIN 19730), where correlation coefficients range between $r=0.62$ and $r=0.85$.

Fig. 6: Variability of zinc concentrations during percolation of a undisturbed soil column under unsaturated conditions

Fig. 7: Comparison of zinc concentrations of percolates from soil column tests with in-situ samples (all data related to Hilbersdorf test site)
Tab. 3: Regression equations for the conversion of mobilizable metal contents into leachate concentrations based on DIN 38414 (DEV S4) extraction:

<table>
<thead>
<tr>
<th>Element</th>
<th>Equation</th>
<th>Correlation Coefficient r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>$y = 0.487 \times$</td>
<td>0.49</td>
</tr>
<tr>
<td>As</td>
<td>$y = 0.017 \times$</td>
<td>0.48</td>
</tr>
<tr>
<td>Cu</td>
<td>$y = 0.048 \times$</td>
<td>0.78</td>
</tr>
<tr>
<td>Pb</td>
<td>$y = 0.021 \times$</td>
<td>0.54</td>
</tr>
<tr>
<td>Zn</td>
<td>$y = 0.584 \times$</td>
<td>0.60</td>
</tr>
</tbody>
</table>

based on DIN V 19735 extraction:

<table>
<thead>
<tr>
<th>Element</th>
<th>Equation</th>
<th>Correlation Coefficient r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>As</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cu</td>
<td>$y = 0.558 \times$</td>
<td>0.50</td>
</tr>
<tr>
<td>Pb</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zn</td>
<td>$y = 2.219 \times$</td>
<td>0.70</td>
</tr>
</tbody>
</table>

based on DIN 19730 (NH$_4$NO$_3$-) extraction:

<table>
<thead>
<tr>
<th>Element</th>
<th>Equation</th>
<th>Correlation Coefficient r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>$y = 0.018 \times$</td>
<td>0.64</td>
</tr>
<tr>
<td>As</td>
<td>$y = 0.181 \times$</td>
<td>0.62</td>
</tr>
<tr>
<td>Cu</td>
<td>$y = 0.177 \times$</td>
<td>0.77</td>
</tr>
<tr>
<td>Pb</td>
<td>$y = 0.006 \times$</td>
<td>0.85</td>
</tr>
<tr>
<td>Zn</td>
<td>$y = 0.032 \times$</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Fig. 8: Zinc concentrations of percolating soil water at unsaturated, steady-state flow conditions as a function of corresponding mobilizable metal contents.
Transfer on regional scale. The Saxonian agency for Environment and Geology (Sächsisches Landesamt für Umwelt und Geologie) conducted a comprehensive measuring program in the years 1993-2004 in order to evaluate the heavy metal load of saxonian soils. Based on a 4x4km grid total as well as \( \text{NH}_4\text{NO}_3 \) mobilizable metal contents were determined for topsoil and subsoil samples. Altogether 2584 samples were taken at 1164 locations (Sächsisches Landesamt für Umwelt und Geologie 2000). By adding further monitoring data available at the agency a total of 4600 topsoil samples are available referring to topsoil \( \text{NH}_4\text{NO}_3 \) mobilizable metal contents.

Applying the regression equations as compiled in table 2 to the bulk of topsoil \( \text{NH}_4\text{NO}_3 \) mobilizable contents the resulting soil water concentrations are aggregated to a set of maps showing the topsoil metal concentrations for the entire state of Saxony. As an example Fig. 9 plots the calculated zinc concentrations which vary between 0.4\( \mu \text{g/l} \) and 4450 \( \mu \text{g/l} \). Mean concentration accounts for 63.6 \( \mu \text{g/l} \). Due to the former lead and silver mines and smelter plants highest zinc concentrations are found around the city of Freiberg and along the downstream section of the Freiberger Mulde river where eroded soils including particle bound metals are deposited within the flood plane. According to the respective German legislation (BBodSchV 1999) a zinc concentration of \( >500 \mu \text{g/l} \) is associated to a considerable risk of groundwater pollution. Taking the calculated topsoil zinc concentrations as reference this threshold might be exceeded around the city of Freiberg and the downstream Mulde flood plain.

In a subsequent step leaching rates were calculated by multiplying the calculated metal concentrations with spatially distributed groundwater recharge rates which are also provided by the Saxonian state agency (Sächsisches Landesamt für Umwelt und Geologie 2007). Fig. 10 presents the
resulting map for the leaching of zinc. Calculated losses of zinc approach a maximum of 10000 g/(ha·a). However, mean loss amounts to 95 g/(ha·a). As expected highest losses occur in the area of Freiberg and the downstream flood plane of the Mulde river.

With regard to the calculated topsoil losses the question arises to which extent the leached metals enters the surface water system by subsurface respectively groundwater transport. To answer that question the topsoil losses were added up for the Mulde river basin and compared to the long-term mean metal discharges measured at the catchment outlet. Some results are compiled in Fig. 11. Total mass rates (output) of Zn and Pb are provided by the Elbe River Council (Flussgebietsgemeinschaft Elbe). Although anthropogenic contaminants in surface waters (point sources) have been reduced by more than 90% during the past decades the total output from the Mulde basin has to be reduced by the population related inputs which amount to less than 6 t/a Zn and less than 1 t/a Pb. Comparing the resulting geogenic output with the calculated sum of topsoil losses reveals that subsoil retention amounts to 27% of topsoil losses for Zn respectively 84% for Pb. Actually the expected subsoil retention for Pb should be much higher than for Zn because the mobility of Zn in soils is substantially higher than those of Pb as commonly known (Li & Shuman 1996). Therefore received results seem to be plausible with respect to subsurface retention.

Fig. 10: Loss of Zinc by leaching of topsoils

CONCLUSIONS
In contrast to in-situ soil water sampling laboratory tests of heavy metal mobility are only an incomplete reproduction of natural conditions. Their advantage, however, is the reduction of the various natural impacts (e.g. weather conditions) to a small number of parameters that can be controlled and varied systematically. Simple standard methods such as the NH4NO3 – extraction cover the pool of mobile element fractions of a soil. Those methods are very well adapted for surveying heavy metals on regional scale.

Unsaturated steady-state column tests using undisturbed samples are capable to reproduce mean long term heavy metal concentrations in percolating soil water adequately. These tests provide the best representation of natural conditions under laboratory conditions, but they are time consuming and expensive. Using both - standard extraction methods and soil column tests - this study derives a set of empirical relationships that are successfully used to estimate top soil heavy metal concentrations and leaching losses on regional scale. The transport of heavy metals to ground respectively surface waters was assessed by comparing the calculated top soil metal losses with the metal discharge at the outlet of an exemplary river catchment. Results prove different retention losses dependent on metal species. Retention of Pb is much higher than that for Zn.

Fig. 11: Mass rates of Zn and Pb related to the Mulde river basin assign to different sources (Source: Flussgebietsgemeinschaft Elbe 2012)

ACKNOWLEDGEMENTS

The authors thank the Agency for Environmental Protection Baden-Württemberg (Landesanstalt für Umweltschutz Baden-Württemberg) and the Saxonian Agency for Environment and Geology (Sächsisches Landesamt für Umwelt und Geologie) for financial support and the Elbe River Council for providing data.

REFERENCES

Beesley, L., Moreno-Jiménez, E., Clemente, R., Lepp, N., Dickinson, N. 2010: Mobility of arsenic, cadmium and zinc in a multi-element contaminated soil profile assessed by in-situ soil pore water sampling, column leaching and sequential extraction, Environmental Pollution, Volume 158, Issue 1, pp. 155-160


DIN V19735 1999: „Ableitung von Konzentrationen im Bodenwasser aus ammoniumextrahierbaren Gehalten oder Eluatgehalten“, Berlin

DIN 138414-4 (1984): „Schlamm und Sedimente (Gruppe S) Bestimmung der Eluierbarkeit mit Wasser (S 4)“, Berlin


Sächsisches Landesamt für Umwelt und Geologie 2000: Bodenatlas des Freistaates Sachsen - Teil 3: Bodenmeßprogramm

Sächsisches Landesamt für Umwelt und Geologie 2007: Bodenatlas des Freistaates Sachsen -Teil 4: Auswertungskarten zum Bodenschutz
