Biochar is a by-product of fuel production from organic waste and energy crops via pyrolysis or similar processes. Biochar is also considered as a soil modifier, in particular due to:
- its fertilizing effect and
- its potential for long-term carbon storage.

Thus, biochar can contribute to enhanced biomass production and to the reduction of carbon dioxide in the atmosphere. Although it has been intensively investigated since some years with various methods, there is still many open questions concerning its influence on soil properties. Methods which allow investigations in the laboratory under defined conditions and in the field are particularly interesting.

Spectral induced polarization (SIP) determines the effective complex electrical conductivity $\sigma = \sigma' + i \sigma''$. The real part $\sigma'$ is the ohmic conductivity due to polarization effects in the pore space of the soil. It provides a phase shift between current and voltage like a capacitor in an electrical circuit.

Electrical impedance tomography (EIT) is an extension of SIP that allows imaging the spatial distribution of $\sigma''$. SIP and EIT are geoelectrical methods developed for large-scale application. They are known as techniques for ore exploration already since the beginning of the 20th century. Both methods can now also be favorably used for the investigation of soil properties and processes in the vadose zone due to the considerable improvement of electronic equipment [1].

### Properties of Biochars

The conditions for pyrolysis (temperature and contact time) and the hydrogen content of the biochars are very different (Table 1). The H/C molar ratio decreases with increasing temperature and contact time during pyrolysis.

<table>
<thead>
<tr>
<th>biochar</th>
<th>pyrolysis temperature / °C</th>
<th>pyrolysis contact time / s</th>
<th>hydrogen content / % (w/w)</th>
<th>carbon content / % (w/w)</th>
<th>H/C atomic ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>biochar 1</td>
<td>450 - 500</td>
<td>unknown</td>
<td>3.37 ± 0.02</td>
<td>70.0 ± 1.0</td>
<td>0.578</td>
</tr>
<tr>
<td>biochar 2</td>
<td>500</td>
<td>13 - 18 Hz</td>
<td>2.67 ± 0.04</td>
<td>67.4 ± 0.7</td>
<td>0.436</td>
</tr>
<tr>
<td>biochar 3</td>
<td>500</td>
<td>1 s</td>
<td>2.60 ± 0.05</td>
<td>75.9 ± 1.5</td>
<td>0.569</td>
</tr>
<tr>
<td>biochar 4</td>
<td>1100</td>
<td>30 s</td>
<td>2.15 ± 0.12</td>
<td>70.4 ± 0.4</td>
<td>0.258</td>
</tr>
<tr>
<td>biochar 5</td>
<td>800</td>
<td>20 min</td>
<td>0.5</td>
<td>74.4 ± 0.5</td>
<td>0.081</td>
</tr>
</tbody>
</table>

### Spectra of Complex Electrical Conductivity

Biochar 4 shows high values for $\epsilon''$ as well as for $\epsilon'$. Both the real (Figure 1a) and the imaginary part (Figure 1b) of conductivity are higher for the sand-biochar mixture than for sand alone. The arrow indicates the direction of the frequency change for the first half of the measurement cycle. The ohmic conductivity $\sigma'$ increases during the first measurement cycle from large to low and again to high frequencies due to the release of ions.

Spectra of biochars exhibit considerably lower polarization expressed by $\epsilon''$, but all values are increased above about 1 Hz (Figure 2). The time dependence of $\epsilon''$ for biochar 4 is shown in Figure 3. The release of ions lasts for about 3 days. Scattering data are due to temperature effects which could not be fully compensated in a temperature range between 20 and 21 °C.

SIP Measurements on Biochars

The complex electrical conductivity $\sigma''$ was determined for mixtures of sand (grain size 125-250 µm) and 2 % biochar saturated with 4 mM NaCl solution in the frequency range from 1 mHz to 45 kHz. Spectra of the real part of the conductivity $\sigma'$ and the imaginary part of the conductivity $\sigma''$ of biochar 4 are shown in Figure 1a.

All biochars show an increase of the real part of electrical conductivity $\sigma'$ with time indicating the release of ions from the carbon material like biochar 4 (Figure 1a). Figure 1b shows the imaginary part of conductivity $\sigma''$ for biochar 4.

The spectra of the imaginary part of conductivity $\epsilon''$ for all biochars are shown in a double logarithmic plot in Figure 2.

Figure 3 shows the real part of the conductivity $\sigma'$ for biochar 4. At higher frequency (above 1000 Hz), Maxwell-Wagner polarization becomes more and more important. This type of polarization is due to differences of conductivities and dielectric constants in mixtures of materials. It is particularly large, when electronic conduction is involved. Since graphite is an electronic conductor, biochar is expected to exhibit enhanced conduction compared with sand. The effect should be the larger, the more similar the structure of charcoal is to graphite.

The molar ratio of hydrogen and carbon in the biochar is the measure of carbonization. The lower this quantity is, the nearer the structure of the charcoal is to graphite.

Biochar 4 and an active carbon with similar values of $\sigma''$ and different values of $\sigma'$ were used for a 2D experiment with EIT [2]. Structures of the mixtures of sand and 2 % charcoal were built into a sand matrix saturated with 4 mM NaCl (Figure 7a). The elevated $\sigma'$ values of both mixtures can be well observed in the image obtained in the inversion result that used electrical measurements for biochar 4 with a set of 16 electrodes (Figure 7b). The two different mixtures can also well be distinguished by the image of $\epsilon''$ at 100 Hz (Figure 7c). Biochar 4 with its very strong polarization is well visible in the center of the cylindrical sample holder, but also active carbon with much lower value of $\epsilon''$ can be detected. The values of $\sigma''$ and $\epsilon''$ correspond well with those obtained by the reference SIP measurements.

### Conclusions and Outlook

SIP allows the observation of processes (ion release) and the characterization of biochars concerning:
- particle size and
- degree of carbonization.

EIT allows the localization of biochar in sand and most probably also in soil. It thus enables spatial resolution of processes related to biochars, e.g. ion release.

According to the results of this study, SIP and EIT are suitable to investigate special aspects of biochars in soil. Further experiments on the influence of water saturation seem to be promising for determining hydraulic parameters. Combined measurements of SIP with multiphase outflow and EIT experiments on evaporation are planned. Since both methods can be applied at different scales, SIP and EIT may not only be useful for basic investigations in the laboratory, but also for long-term monitoring in the field.

References