Biochar characterization and impacts on agricultural soils of the temperate region

Effects on soil fertility, crop yield and trace element behavior

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Outline

Introduction
- What is biochar?
- Biochar properties
- The Austrian BIOCHAR project
- Objectives

Results
- Characterization of slow pyrolysis biochars
- Impacts of biochar on soil fertility and plant growth
- Trace element behavior in biochar-amended soils

Conclusions
Introduction

**What is biochar?**

**Pyrolysis**

Thermal decomposition of biomass under low-oxic conditions and relatively low temperatures (< 700°C)

**Biochar**

Carbon-enriched, aromatic solid product resulting from pyrolysis of biomass

→ Soil amendment, C sequestration

Role model: **Amazonian Terra Preta soils**

Anthrosols: Pottery, animal and human waste, **charred organic material**

→ higher pH, increase in Soil organic matter, higher cation exchange capacity

Radiocarbon dating: charcoal up to 7000 years old
Introduction

Biochar properties

FEEDSTOCK
(wood, nutshells, straw, poultry litter)

PYROLYSIS CONDITIONS
(temperature, residence time, heating rate,...)

volatilization, loss of C, N, H, decarboxylation, decarbonylation, dehydration, depolymerization

PYROLYSIS

Biochar properties

Changes in elemental ratios
- decrease of O/C, H/C ratios → stability, aromaticity
  - Stable C pool
  - increase of C/N, enrichment in C

Increase in specific surface area, porosity
- cation exchange capacity, habitat for microorganisms

Increase in pH and ash content
- due to enrichment of alkaline, inorganic compounds

Enrichment of nutrients (but: potentially toxic compounds)

C sequestration potential

Increased water and nutrient holding capacity, soil remediation potential
Introduction

The Austrian BIOCHAR project

“Biochar for Carbon Sequestration in Soils: Analysis of production, biological effects in the soil and economics”

Project period: April 2010 - June 2013

8 work packages:

WP 1: Biomass and pyrolysis conditions for biochar production efficiency

BIOCHAR

WP 2: Experimental setup for carbon sequestration, soil studies and biological effects

WP 3: Stability of biochar carbon pools

WP 4: Response of soil microorganisms to biochar application

WP 5: Soil fertility after biochar applications

WP 6: Effects on non-CO₂ greenhouse gas emissions

WP 7: Economic evaluation of biochar production and application

WP 8: Coordination
**Introduction**

**Objectives**

**Characterization of different biochars**
Influence of **feedstock and pyrolysis temperature**
Formation/accumulation of **potentially toxic compounds**

Kloss et al. (2012), *Journal of Environmental Quality* 41, 990-1000; cited 46 times

- **glasshouse pot experiment**

**Soil fertility/crop growth and composition**

- Varying biochar application rates on different soils (Planosol, Cambisol, Chernozem)
- **Different biochar types on one soil** (Planosol)
- Different N fertilization rates with/without biochar

Kloss et al. (2014), *Journal of Plant Nutrition and Soil Science* 177, 3-15

**Trace element behavior in soil-water-plant system**

- Varying biochar application rates on different soils (Planosol, Cambisol, Chernozem)
- Different biochar types on one soil (Planosol)

Kloss et al. (2014), *Science of the Total Environment* 481, 498-508
Kloss et al. (2014), *Environmental Science and Pollution Research*, under revision.
# Results

**Biochar characterization**

- **Three feedstocks** slowly pyrolyzed
  
  \(\text{Triticum aestivum, populus tremula, picea abies}\)

- **Three pyrolysis temperatures:**
  
  \(400^\circ C, 460^\circ C, 525^\circ C\)

<table>
<thead>
<tr>
<th>Basic characterization</th>
<th>Molecular/ mineralogical characterization</th>
<th>Ecotoxicologically relevant parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>- pH</td>
<td>- Differential Scanning Calorimetry (DSC)</td>
<td>- Water extractable trace elements</td>
</tr>
<tr>
<td>- Electrical conductivity (EC)</td>
<td>- Fourier-Transform Infrared Spectroscopy (FTIR)</td>
<td>- Polycyclic aromatic hydrocarbon (PAH) content and composition (EPA 16)</td>
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<td>- Ash content</td>
<td>- X-ray diffraction (XRD)</td>
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<td>- Cation exchange capacity (CEC)</td>
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<tr>
<td>- Specific surface area (BET-N(_2))</td>
<td></td>
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<tr>
<td>- Total C, N and H</td>
<td></td>
<td></td>
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<tr>
<td>- Water-extractable major elements</td>
<td></td>
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<tr>
<td>- Ash composition (XRF)</td>
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</table>
## Results

### Biochar characterization

#### Basic characterization

<table>
<thead>
<tr>
<th>pyrolysis temperature</th>
<th>pH (CaCl₂)†</th>
<th>EC (mS cm⁻¹)†</th>
<th>ash (wt.%)†</th>
<th>C (wt.%)‡</th>
<th>SSA (m² g⁻¹)‡</th>
<th>CEC (mmol kg⁻¹)‡</th>
<th>PAHs (mg kg⁻¹)‡</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>straw</strong></td>
<td></td>
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<tr>
<td>feedstock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400°C</td>
<td>9.1</td>
<td>1.08</td>
<td>9.7</td>
<td>65.7 ± 1.9 b</td>
<td>4.8 ± 0.5 a</td>
<td>161.6 ± 15.6 e</td>
<td>5.2 ± 2.9 a</td>
</tr>
<tr>
<td>460°C</td>
<td>8.7</td>
<td>4.92</td>
<td>12.0</td>
<td>72.4 ± 4.9 bcde</td>
<td>2.8 ± 1.8 a</td>
<td>117.0 ± 21.2 cd</td>
<td>10.7 ± 5.6 ab</td>
</tr>
<tr>
<td>525°C</td>
<td>9.2</td>
<td>4.43</td>
<td>12.7</td>
<td>74.4 ± 4.9 cde</td>
<td>14.2 ± 4.0 a</td>
<td>97.7 ± 19.4 bc</td>
<td>33.7 ± 22.1 b</td>
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<td><strong>poplar</strong></td>
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<tr>
<td>feedstock</td>
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<td></td>
<td>1.1</td>
<td>46.1 ± 0.8 a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400°C</td>
<td>9</td>
<td>1.04</td>
<td>3.5</td>
<td>67.3 ± 0.8 bc</td>
<td>3.0 ± 0.6 a</td>
<td>144.0 ± 5.6 de</td>
<td>4.3 ± 1.8 a</td>
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<tr>
<td>460°C</td>
<td>9.2</td>
<td>0.70</td>
<td>5.7</td>
<td>70.0 ± 0.0 bcd</td>
<td>8.2 ± 0.1 a</td>
<td>128.3 ± 17.7 cde</td>
<td>17.9 ± 3.6 ab</td>
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<tr>
<td>525°C</td>
<td>8.7</td>
<td>0.86</td>
<td>6.8</td>
<td>77.9 ± 1.0 de</td>
<td>55.7 ± 19.5 b</td>
<td>107.6 ± 7.6 bcd</td>
<td>2.0 ± 0.8 a</td>
</tr>
</tbody>
</table>

† single determination
‡ determined in triplicate (means ± standard deviation)

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Kloss et al. (2012), *Journal of Environmental Quality* 41, 990-1000

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Pyrolysis temperature has important influence on most properties

Accumulation of ash, carbon

Increase of specific surface area, but decrease of CEC
Results

Biochar characterization

Molecular characteristics of poplar feedstock and biochars

Differential scanning calorimetry (DSC)

Fourier-Transform Infrared Spectroscopy (FTIR)

→ Increase in aromaticity/(thermal) stability with increasing pyrolysis temperature

→ Net decrease of functional groups with increasing pyrolysis temperature

Kloss et al. (2012), Journal of Environmental Quality 41, 990-1000
Results

Biochar characterization

Individual PAHs in % of total PAH composition (based on US EPA 16)

=str Increasing dominance of naphthalene with increasing pyrolysis temperature

Kloss et al. (2012), Journal of Environmental Quality 41, 990-1000
Pot experiment: Design

**Four different biochars:**
- Wheat straw [525°C]
- Mixed woodchips [525°C]
- Vineyard pruning [525°C]
- Vineyard pruning [400°C]

**Two application rates:**
- 1 and 3 w.-%
- (equals 30 and 90 t ha⁻¹)

**Three soils:**
- Planosol (sandy loam, pH 5.4)
- Cambisol (clay loam, pH 6.6)
- Chernozem (silt loam, pH 7.4)

**Three successive crops:**
- Mustard (*Sinapis alba* L.)
- Barley (*Hordeum vulgare* L.)
- red clover (*Trifolium pratense* L.)

**GEOLOGY**
- Granite / gneiss
- Tertiary sediments
- Loess

**Start in Nov. 2010**
- fertilization:
  - Mustard: 40 kg N ha⁻¹
  - barley: 100 kg N ha⁻¹
Pot experiment: Analyses

Effects on soil fertility and crop yield
- Mustard, barley, clover
  - Above-ground biomass
  - N concentration
  - Elemental composition (full acid digestion; HNO_3:HClO_4)

Effects on trace element behavior
- B, Al, Mn, Cu, As, Se, Mo, Cd, Pb

Soil-biochar mixtures
- pH, electrical conductivity
- C/N
- Cation exchange capacity
- CAL-extractable P and K
- Nitrogen supplying potential

Mustard
- Trace elements (full acid digestion; HNO_3:HClO_4)

Biochar analyses
- pH, electrical conductivity, cation exchange capacity, C/N, specific surface area

Soil-biochar mixtures
- NH_4NO_3-extractable trace elements
- Cd and Cu sorption

Biochar analyses
- Water and Aqua Regia extractable trace elements

Leachates
- Trace elements
Results

Soil fertility and crop growth

Effects of different biochars on Planosol

→ Significant increase of pH and CEC for all BC types on the acidic sandy Planosol

→ Increase in P and K extractability (CAL) (esp. straw)

No influence of pyrolysis temperature!

(after 7 months)

Kloss et al. (2014), Journal of Plant Nutrition and Soil Science 177, 3-15
Results

Soil fertility and crop growth

Effects of different biochar types on crop yield (Planosol)

- Initially detrimental effects (except for straw biochar)
- Significant increase in above-ground biomass on wheat straw biochar amended soil for second crop

Influence of pyrolysis temperature

Kloss et al. (2014), Journal of Plant Nutrition and Soil Science 177, 3-15
Results

Soil fertility and crop growth

“BC application to soil causes N deficiency in plants” (Rondon et al., 2007; Collison et al., 2009, …)

“pH increase may cause micronutrient deficiencies” (Marschner and Rengel, 2012)

N concentration in mustard

Soil nitrogen supplying potential

No or negligible N-immobilization; increased nitrogen supplying potential (except for VP400)

Micronutrient deficiency?

Kloss et al. (2014), Journal of Plant Nutrition and Soil Science 177, 3-15
Results

Trace element behavior

Kloss et al. (2014), Environmental Science and Pollution Research (in review)
Results

Trace element behavior

Kloss et al. (2014), *Environmental Science and Pollution Research* (in review)
SUMMARY

Biochar characterization

Properties of biochar dependent on feedstock and pyrolysis temperature (CEC, SSA, ash content)

Increased C content and aromaticity

USEPA PAH limit in biosolids (6 mg kg\(^{-1}\)) clearly exceeded (up to 33.7 mg kg\(^{-1}\) in straw biochar); change of PAH composition → ecotoxicologically relevant

All biochar types positively affected soil pH, cation exchange capacity of an acidic Planosol

Short-term detrimental effects on crop yield upon biochar application (except wheat straw biochar)

Biochar application affected trace element behavior, partly due to a direct input of trace elements
CONCLUSIONS

The application of biochar on temperate as a soil amendment may be overall less favorable than in tropical soils (role model Terra Preta), but strongly depends on biochar and soil type.

In temperate regions, the “amendment effect” may be limited to degraded soils.

Potential soil-conditioning effect masked by (short-term) crop decreases
→ Different pre- post treatments; feedstocks, pyrolysis conditions
→ Alternative application purpose

→ Mitigation of climate change
→ Nitrogen use efficiency/ decreased nitrogen loss
→ Soil remediation potential for cationic trace elements (Cd, Pb)
   However: BC application may increase solubility of anionic trace elements (deficiency vs. toxicity)

In view of ecotoxicological relevance: biochar standardization/ quality control

long-term (field) experiments needed (other effects may become relevant → increased water holding capacity)
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