Biochar beyond carbon sequestration: Life-cycle emission reductions, nutrient recycling and food security

Johannes Lehmann

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Biochar Beyond Carbon Sequestration: Life-Cycle Emission Reductions, Nutrient Recycling and Food Security

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Abstract

Biochar is by now recognized as a carbon dioxide removal (CDR) approach in climate change mitigation scenarios. Less clear is its framing as an approach for soil carbon sequestration. We posit that biochar carbon sequestration has all the traits of CDR through soil carbon management, with respect to greenhouse gas abatement and co-benefits for food production. Similar to compost, biochar is typically produced off-soil, and a life-cycle emission balance is required to quantify impact. The fact that biochar production by pyrolysis can generate energy products from the concurrent evolution of gases may position biochar as a hybrid engineering-biological approach. However, the CDR is still delivered by photosynthesis and biochar improves soil fertility. Here we argue that many forms of SOC sequestration have implicit tradeoffs with food security when they are scaled globally, whereas this is not the case with soil amendments such as biochar or compost from non-competitive biomass resources. Other advantages of biochar for soil carbon sequestration arise from its persistence in soil, allowing one-time or periodic applications, and the capacity to estimate sequestration from the chemical composition of the biochar, both facilitating implementation and avoiding the need for soil sampling for monitoring and verification.
Soil Carbon Sequestration System Types

- Production of amendment (e.g., composting or pyrolysis facility)
- Possible bioenergy production and offset of fossil emissions
- Residue
- CO\(_2\), N\(_2\)O, CH\(_4\)
- Biomass
- Transportation
- Amendments (compost, biochar)
- CO\(_2\)
- CO\(_2\)
- Wetland restoration
- Soil Organic Carbon
- Cropland management
- Fertilizer
- Residue
- CO\(_2\), N\(_2\)O, CH\(_4\)
- Soil System
- Landfill
- Other uses
- Bioenergy
- CO\(_2\), N\(_2\)O, CH\(_4\)
- Biomass System
- Largeness
- Pollution
Biochar Climate Mitigation

Two Entry Points:
A: Soil CDR and emission reduction through pyrolysis:
   reduce CO₂/N₂O/CH₄ return of the charred OM
B: Soil CDR and emission reduction through soil application:
   B1: reduce soil GHG emissions (CO₂/N₂O/CH₄)
   B2: increase CO₂ capture by plants through photosynthesis

Lehmann, 2007
Crop Yield Responses

Global crop yield responses
+11-28% (meta-analyses†)

Soil productivity value

‡Jeffery et al. 2011 AEE, 2015; 2017
Env Res Lett; Liu et al., 2011; Ye et al., Soil Use Manage in press
Molecular Properties - Persistence

Low temperature

“Small” cluster sizes:
18-40 C from oak wood and corn residues at 350°C and 600°C
25 to 52 C from chestnut wood between 500°C and 700°C
20 or more C in Midwestern Mollisol and Amazonian Dark Earth

High temperature

Nguyen et al, 2010, EST 44, 3324–3331
McBeath et al, 2011, OG 42, 1194-1202
Mao et al, 2012, EST 46, 9571-9576
Persistence in Soil

Biochar with higher condensation (=low H/Corg ratios) have greater persistence

\[ MRT = 4501e^{-3.2(H/C_{org})} \]

\[ r^2 = 0.16 \]

\[ n = 43, \ p < 0.05 \]

(Only experiments longer than one year, 2-pool model, 10°C)

Lehmann et al, 2015, Routledge
Persistence in Soil

Higher pyrolysis temperature ≈ higher condensation

Opportunities for monitoring practice

Challenge for validating persistence over centuries and millennia

New IPCC guidelines for GHG accounting

(Only experiments longer than one year, 2-pool model, 10°C)

Major et al. 2010; Zimmerman 2010; Singh et al. 2012; Zimmerman & Gao 2013; Fang et al. 2014; Herath et al. 2015; Kuzyakov et al. 2014; Dharmakeerthi et al. 2015

EQUATION 4A.1

ANNUAL CHANGE IN BIOCHAR CARBON STOCK IN MINERAL SOILS RECEIVING BIOCHAR ADDITIONS

\[
\Delta \text{BC}_{\text{Mineral}} = \sum_{p=1}^{n} \left( B\text{C}_\text{TOT}_p \cdot F_{C_p} \cdot F_{\text{perm}_p} \right)
\]
### TABLE 4A.1
VALUES FOR ORGANIC C CONTENT FACTOR OF BIOCHAR BY PRODUCTION TYPE ($F_{Cp}$).

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Pyrolysis Production Process</th>
<th>Values for $F_{Cp}$ $^{1,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal manure</td>
<td>Pyrolysis $^1$</td>
<td>0.38 ± 49%</td>
</tr>
<tr>
<td></td>
<td>Gasification $^1$</td>
<td>0.09 ± 53%</td>
</tr>
<tr>
<td>Wood</td>
<td>Pyrolysis</td>
<td>0.77 ± 42%</td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td>0.52 ± 52%</td>
</tr>
<tr>
<td>Herbaceous (grasses, forbs, leaves; excluding rice husks and rice straw)</td>
<td>Pyrolysis</td>
<td>0.65 ± 45%</td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td>0.28 ± 50%</td>
</tr>
<tr>
<td>Rice husks and rice straw</td>
<td>Pyrolysis</td>
<td>0.49 ± 41%</td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td>0.13 ± 50%</td>
</tr>
<tr>
<td>Nut shells, pits and stones</td>
<td>Pyrolysis</td>
<td>0.74 ± 39%</td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td>0.40 ± 52%</td>
</tr>
<tr>
<td>Biosolids (paper sludge, sewage sludge)</td>
<td>Pyrolysis</td>
<td>0.35 ± 40%</td>
</tr>
<tr>
<td></td>
<td>Gasification</td>
<td>0.07 ± 50%</td>
</tr>
</tbody>
</table>

### TABLE 4A.2
VALUES FOR $F_{perm}$ (FRACTION OF BIOCHAR C REMAINING AFTER 100 YEARS)

<table>
<thead>
<tr>
<th>Production</th>
<th>Value for $F_{perm}$ $^{1,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High temperature pyrolysis and gasification (&gt; 600 °C)</td>
<td>0.89 ± 13%</td>
</tr>
<tr>
<td>Medium temperature pyrolysis (450-600 °C)</td>
<td>0.80 ± 11%</td>
</tr>
<tr>
<td>Low (350-450 °C)</td>
<td>0.65 ± 15%</td>
</tr>
</tbody>
</table>
Mineralization of Existing Soil OC by Biochar

Average mineralization reduction: -3.8%
(95% CI = -8.1–0.8%)

Wang et al., 2016 Global Change Biology 8, 512-523
Whitman et al, 2015, Routledge
Primimg of Existing Soil OC by Biochar

Greater SOC while root biomass unchanged

Negative priming of SOM by 6% and increased recovery of root-derived C by 20%

Nine years after one-time biochar application of 10 t ha\(^{-1}\)

Weng et al., 2017 Nature Climate Change 7, 371-376
Soil Nitrous Oxide Emissions with Biochar

Average net reduction 54%

(BUT: typically no isotope studies
BUT: wrong control)

(n=30 studies)

Cayuela et al. 2014, Agr. Ecosys. Env. 191, 5-16
Biochar as a Soil Amendment

**Carbon Product**
- Carbon persistence
- Surface area and functional groups
- Electron shuttle and fused arom.

**Nutrient Product**
- Nutrient enrichment
- Nutrient availability
- Sterilization
- Denaturing of pollutants

- GHG reduction + C sequestration
- Soil Health
- Pollution reduction by leaching and gas emissions
- Soil remediation
- Inoculant carriers
- Signaling (plant-plant; plant-MO)

**Fertilization**
- Pollution avoidance
- GHG reduction (+ C sequestration)
Global Supplies and New York Phosphate

Cordell et al. 2011, *Sustainability* 3, 2027-2049
Ketterings and Czymmek K 2012 *What’s Cropping Up*
Recycling of Dairy Manure using Pyrolysis

No contaminants (heavy metal, PAH, PCB, dioxin/furans, etc.)
No pollutants from manure (pathogens, hormones, antibiotic)

100 kg liquid dairy manure
0.1% phosphorus

4 kg biochar
2% phosphorus

www.pyrolysis.cals.cornell.edu

Recycling of Dairy Manure using Pyrolysis

Value as ingredient of potting mix: appr. $1,900 ton\(^{-1}\)
83% from C value (as potting mix)

Maximum Potential (NYS per year):
$272M value for farmer
$1.3B value for retail
$114M reduced transportation
$4-15M reduced GHG ($20-80/t CO\(_2\)e)

Nutrients better available to plants, but less leachable!

<table>
<thead>
<tr>
<th>Element</th>
<th>Manure</th>
<th>Biochar</th>
<th>Change due to pyrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leachable</td>
<td>Available</td>
<td>Leachable</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>409.8</td>
<td>4505.9</td>
<td>35.8</td>
</tr>
<tr>
<td>Potassium</td>
<td>7372.8</td>
<td>8114.2</td>
<td>9399.9</td>
</tr>
<tr>
<td>Calcium</td>
<td>31257.5</td>
<td>80671.0</td>
<td>33720.8</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2785.9</td>
<td>6578.6</td>
<td>291.1</td>
</tr>
</tbody>
</table>

Biochar as Adsorber

<table>
<thead>
<tr>
<th>Biochar</th>
<th>Solution</th>
<th>Total N before urine (%w/w)</th>
<th>Total N after urine (%w/w)</th>
<th>ΔN after urine (%w/w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500°C HSW</td>
<td>Fresh urine + HCl</td>
<td>3.33 ± 0.08</td>
<td>4.47 ± 0.17</td>
<td>1.14 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>Fresh urine</td>
<td></td>
<td>3.59 ± 0.05</td>
<td>0.26 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>Deionized water</td>
<td></td>
<td>3.71 ± 0.02</td>
<td>0.38 ± 0.08</td>
</tr>
</tbody>
</table>

- N retention primarily NH$_4^+$ at pH <7
- Greater than predicted by CEC, 1.14% vs. 0.31% (w/w)
Biochar Oxidation and NH$_3$ Retention

Up to 18% N

Hestrin et al, 2019, *Nature Communications* 10, 664
Biochar Oxidation and NH₃ Retention

>50% N retained through chemisorption rather than physisorption
>10% in heterocyclic structure
Biochar as Nitrogen Adsorber

Biochar from N-rich human solid waste (solid-liquid separating toilets, Nairobi)
Biochar as Nitrogen Adsorber

- 3% weight increase, 15 mg/g N increase
- 15% weight increase, 50 mg/g N increase

Krounbi et al., submitted
Biochar as Nitrogen Adsorber

>7 µm depth of NH₃ into biochar material
Poultry Litter Processing
Environmental Benefits

Lei, Bora et al., 2019, in preparation

-752 kg CO2-eq/ton manure
Climate Change Mitigation – Life Cycle

Manure wastes missing in global assessments

Take-Home Messages

- Biochar system with nutrient-rich feedstocks delivers resource as well as GHG benefits
  - BUT: technology development needed

- Lower life-cycle emission reductions of biochar systems than SOC accrual alone
  - BUT: Lots of moving parts that need monitoring (N$_2$O, time horizon…), not only with biochar systems…

- Trade-offs between food production and C accrual is different between external and internal C source approaches and environmental/water burden not considered
  - BUT: Yield/water prioritization of land managers/costs