Biochar: What is it and what can it do?

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Agricultural Research Service (ARS)

- In-house scientific research agency for the United States Department of Agriculture (USDA).

  Goal: Finding solutions to agricultural problems that affect Americans every day, from field to table

- 2,500 scientists
- 6,000 other employees
- 1,000 research projects within 20 National Programs
- 100 research locations including a few in other countries
- $1.1 billion (USD) fiscal year 2012 budget
MISSION: Develop and evaluate agricultural management practices that optimize production while reducing impacts on air, soil and water quality.
Step 1. Biochar: What is it?
Carbon (many forms)
Biomass Carbon
Black Carbon

• *Black carbon* is the range of solid residual products resulting from the chemical and/or thermal conversion of any carbon containing material (e.g., fossil fuels and biomass) (Jones et al., 1997)
Problem → Lack of nomenclature uniformity

Adapted from Hedges et al., 2000; Elmquist et al., 2006; Spokas, 2010
Formation of Black Carbon: “Pyrolysis”

- **Pyrolysis** is the chemical decomposition of an organic substance by heating
- **Does not** involve reactions with oxygen
  - Typically in the absence of oxygen
- Pyrolysis is also used in everyday activity – *Cooking* → *roasting, baking, frying, grilling*
- Also occurs in lava flows and forest/prairie fires
Overview of Pyrolysis

Biomass → Pyrolysis → Building Blocks

- Gas (syngas)
- Liquid (bio-oil)
- Solid (black carbon)

Tear apart and reorganize → Form new compounds and chemicals
Both temperature and time factors:

- **High temperature pyrolysis**
  - gasification (>800 °C) \(+ \text{O}_2\)

- **“Fast” or “Slow” pyrolysis (300-600 °C)**
  - **Fast pyrolysis**
    - 60% bio-oil, 20% biochar, and 20% syngas
    - Time = seconds
  - **Slow pyrolysis**
    - Can be optimized for char production
      (>40% biochar yields)
    - Time = hours
Pyrolysis unit in Florence, SC
(USDA-ARS)
Others Ways to Make Black Carbon
1998 - First use of *biochar* to describe the solid residue in scientific literature from biomass pyrolysis (Bapat and Manahan, 1998)

Dec. 2008 – Biochar linked in newsfeed story as a potential abatement to climate change; even though scientifically was mentioned over 20 years prior (~1985)
Biochar – Returned Web Results

Jan 08 – 285 web hits → Jan 2012 approx. 2.87 million return hits

Jan 2008 – 285 results

Jan 2012 – 2.87 million results
Back to Google Search Trends

![Graph of Black Carbon search trends from Jan 2004 to Aug 2011.](image1)

![Graph of Charcoal search trends from Jan 2004 to Aug 2011.](image2)
Biochar: New purpose not a new material

• We have used black carbon in the past….and currently

Cave Drawings (>10,000 to 30,000 BC)

Used as fuel (3000-4000 BC)

Water filtration (2000 BC)

Charcoal production (15th century)

Pencils – 2012
What is new?

The use (or purpose) for the creation of charred biomass:

**Atmospheric C sequestration**

Dates to 1980’s and early 2000’s

(Goldberg 1985; Kuhlbusch and Crutzen, 1995; Lehmann, 2006)
Carbon Cycle (+ Biochar)

Lehmann 2006
# Carbon Sequestration: Storage of C

## Carbon Sequestration Rates

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Range of CO₂ Sequestration Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(metric tons C/acre/yr)</td>
</tr>
<tr>
<td>Cropland</td>
<td>0.2 to 0.6 [0.5]</td>
</tr>
<tr>
<td>Grassland / Prairie</td>
<td>0.1 to 1.0 [0.8]</td>
</tr>
<tr>
<td>Forest</td>
<td>0.05 to 4.0 [1.2]</td>
</tr>
<tr>
<td>Swamp / Floodplain / Wetland</td>
<td>2.2 to 3.7 [3.0]</td>
</tr>
</tbody>
</table>
Biochar: Black Carbon Continuum

Biochar – Spans across multiple divisions in the Black C Continuum

However, biochar is NOT a new division or material…

Adapted from Hedges et al., 2000; Elmquist et al., 2006
Biochar: Majority still show relic structures in the biochar
Black Carbon “Spectrum”

Thermo-chemical conversion products

Graphite

Oxygen to carbon (O:C) molar ratio

0 0.25 0.5 0.75 1.0

Soot
Charcoal
Char
Biomass

Complete new structure
Retains relic forms of parent material

Combustion residues
Combustion condensates

Adapted from Hedges et al., 2000; Elmquist et al., 2006; Spokas, 2010
Gaining significant attention:

1. **Carbon Storage**
   - Biochar can store atmospheric carbon, potentially providing a mechanism for reduction in atmospheric CO$_2$ levels

2. **Soil Improvements**
   - Improve water quality
   - Improve soil fertility
   - Reduce GHG emissions

3. **Bioenergy**
Biochar (Summary)

- Solid residue remaining after the heating of biomass materials (renewable) without oxygen (incomplete combustion) for the purpose of carbon sequestration

Biomass Materials

Easily degradable (0-5 yrs)

Pyrolysis

Recalcitrant carbon form (black carbon) (>50 to 1,000,000 yrs?)
Biochar: Soil Application

• The assumed target for biochar has been soil

• Focus has been on “creating” Terra Preta soils

Observations of increased soil fertility and productivity. Postulated from ‘slash and burn’ historic charcoal additions
Comparisons of “Natural” vs. Synthetic Biochar

<table>
<thead>
<tr>
<th>Natural Black Carbon (Biochar?)</th>
<th>Synthetic (Pyrolysis) Biochar</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Heterogeneous feedstock</td>
<td>- Pure homogeneous feedstock</td>
</tr>
<tr>
<td>- Impurities</td>
<td></td>
</tr>
<tr>
<td>- Soil and oxygen</td>
<td></td>
</tr>
<tr>
<td>- Minerals (metals) alter yields</td>
<td></td>
</tr>
<tr>
<td>(e.g. Robertson, 1969; Bonijolya et al., 1982; Baker, 1989)</td>
<td></td>
</tr>
<tr>
<td>- Multiple feedstock sources</td>
<td></td>
</tr>
<tr>
<td>- Species and types</td>
<td></td>
</tr>
<tr>
<td>- Variable temperature</td>
<td>- “Constant” temperature</td>
</tr>
<tr>
<td>- 80 to 1000 °C</td>
<td>- Industrial Process</td>
</tr>
<tr>
<td>- Air cooled/Precipitation/Solar (UV)</td>
<td>- Typically cooled under anaerobic conditions (no water)</td>
</tr>
<tr>
<td>- Exposed to environmental conditions</td>
<td></td>
</tr>
</tbody>
</table>
However, on the other side:

- **Wood distillation plants [1800-1950’s]**
  - Wood pyrolysis – source of chemicals and energy prior to petroleum (fossil fuels)
  - Some historic plants on US-EPA Superfund site list

- **Other charcoal sites**
  - Not always productive
    - Reduced seed germination
    - Reduced plant growth

(BEGLINGER AND LOCKE, 1957)
Applications date back to the beginning of modern science [1800’s]:

Ashes (see also Potash) “constitute an important class of manures, differing, however, in their effects according to the substance which has undergone the process of burning, and the manner in which the process has been accomplished. The ashes of all vegetable substances consist principally of those substances which plants require, as charcoal, lime, phosphoric acid, and alkaline salts. Of these charcoal or carbon is the most valuable, and hence to secure it in the greatest quantity the process of burning should be carried on as slowly as possible, and this is best effected by covering up the mass while burning and admitting no more air than just sufficient to keep up a smouldering fire. The ashes of all vegetables contain almost the same constituent parts, and are found useful in all soils and to the majority of crops. They should always be applied when newly burned, as they lose much of their value by keeping even although kept under cover. A medium quantity of ashes may be taken as 1 lb. weight to the square yard.”* Coal ashes finely screened are also useful as manure, but less so than wood ashes. The ashes of sea weed, known in England as kelp, contain carbonate of soda and salts of potash, and are much used for manure.

(LeFroy, 1883)

Quote is from a 1833 report
Application rate ≈5000 lb/ac (5500 kg/ha)
Applications date back to the beginning of modern science [1800’s]:

And even earlier…

- Fire pits built on soil…

- Ancient Egyptians - pyroligneous acid (bio-oil) - used for embalming
Recent review of historical and recent biochar applications:

- 50% positive,
- 30% no effect, and
- 20% negative impacts on growth and/or yield (Spokas et al., 2011)

However, *should not be used as a basis for forecasting outcomes* → *Publication bias* (Møller and Jennions, 2001)
Proposed Biochar Mechanisms

1. Alteration of soil physical-chemical properties
   - pH, CEC, decreased bulk density, increased water holding capacity
2. Biochar provides improved microbial habitat
3. Sorption/desorption of soil GHG and nutrients
4. Indirect effects on mycorrhizae fungi through effects on other soil microbes
   - Mycorrhization helper bacteria → produce furan/flavoids beneficial to germination of fungal spores

Warnock et al. (2007)
Biochar: Soil Stability

➢ Over a 100 year history of research

Potter (1908) – Initial observation of fungi/microbial degradation of lignite (low grade coal/black carbon)

<table>
<thead>
<tr>
<th>Biochar Degradation Study</th>
<th>Residence Time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steinbeiss et al. (2009)</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Hamer et al. (2004)</td>
<td>40 to 100</td>
</tr>
<tr>
<td>Bird et al. (1999)</td>
<td>50-100</td>
</tr>
<tr>
<td>Lehmann et al. (2006)</td>
<td>100’s</td>
</tr>
<tr>
<td>Baldock and Smernik (2002)</td>
<td>100-500</td>
</tr>
<tr>
<td>Hammes et al. (2008)</td>
<td>200-600</td>
</tr>
<tr>
<td>Cheng et al. (2008)</td>
<td>1000</td>
</tr>
<tr>
<td>Harden et al. (2000)</td>
<td>1000-2000</td>
</tr>
<tr>
<td>Middelburg et al. (1999)</td>
<td>10,000 to 20,000</td>
</tr>
<tr>
<td>Swift (2001)</td>
<td>1,000-10,000</td>
</tr>
<tr>
<td>Zimmerman (2010)</td>
<td>100’s to &gt;10,000</td>
</tr>
<tr>
<td>Forbes et al. (2006)</td>
<td>Millennia based on C-dating</td>
</tr>
<tr>
<td>Liang et al. (2008)</td>
<td>100’s to millennia</td>
</tr>
</tbody>
</table>
Summary of existing literature studies (n=35) on half-life estimation of biochar [Figure from Spokas (2010)]
USDA-ARS Biochar and Pyrolysis Initiative (CHARNet)

16 Locations – Coordinated Multi-location Research Activities
USDA-ARS Biochar and Pyrolysis Initiative (CHARNet)

6 Locations – Coordinated field plot experiment using same hardwood biochar
ARS Biochar Research

Multi-location project

• 6 ARS locations:
  - Ames, IA; Kimberly, ID; St. Paul, MN;
  - Big Spring, TX; Bowling Green, KY; Prosser, WA.
  +additional sites in the near future

• Biochar used in replicated field plots
• Continuous corn (same crop for comparison)
• In addition to following crop yield and soil carbon:
  ✓ Soil gas concentrations and trace gas fluxes
  ✓ Seedling Emergence/Initial seedling growth rates
Biochar Impacts on Soil Microbes & N Cycling

- 90+ different biochars being evaluated
- Over 19 different biomass parent materials
  - Hardwood, softwood, corn stover, corn cob, macadamia nut, peanut shell, sawdust, algae, coconut shell, sugar cane bagasse, switchgrass, turkey manure, chicken feathers, distillers grain
- Represents a cross-sectional sampling of available “biochars”
  - C content 1 to 84 %
  - N content 0.1 to 2.7 %
  - Production Temperatures 350 to 850 °C
  - Variety of pyrolysis processes
    - Fast, slow, hydrothermal, gasification, microwave assisted (MAP)
Ethylene (ethene) Production Rates

Biochar Alone

Biochar + Soil 10% w/w

Spokas et al. (2010)
Ethylene Impacts

Soil Microbial Impacts

- Induces fungal spore germination
- Inhibits/reduces rates of nitrification/denitrification
- Inhibits CH$_4$ oxidation (methanotrophs)
- Involved in the flooded soil feedback

Both microbial and plant (adventitious root growth)
Post-processing of Biochar (Activation)

• Charcoal can be customized in terms of sorptive behavior by activation
  • “Designer Biochar” (J. Novak)
• Processes:
  ➢ Thermal and/or chemical
    • ZnCl₂, steam, acid, base, etc.

• However:
  Surface modification of charcoals also occurs in air at ambient conditions
  3 fold increase in N₂ sorption: 4 year storage (Sheldon, 1920)
MN Department of Agriculture Project

- Examining the bioaccumulation of sorbed chemical species in specialty crops
- Impacts on yield and growth on a variety of crops
- Field and laboratory components
MN Department of Agriculture Project

Sweet Corn Germination

% Germination

Elapse Days

Potting Soil

Soil Control

soil + biochar

Lettuce Germination

% Germination

Elapse Days

Potting Soil

Soil Control

Activated Black Carbon
• Improved & alternative use of distillers grain through microwave assisted pyrolysis

• Examining the potential impacts of distillers grain biochar on soil system – Potential closing the nutrient loop of corn production
So what can I do ???

• Become Involved in Research Efforts
  • Possible participation in collaborative research efforts:

  • **USDA-ARS**
    Kurt Spokas
    kurt.spokas@ars.usda.gov

  • **University of MN Extension Service**
    Regional project: Biochar impacts/feedstock dependencies
    Lynne Hagen
    Lynne.Hagen@co.anoka.mn.us

• “Start wherever you are and start small.”
  Rita Baily
Conclusions

• Biochar is not a new material – new purpose

• No absolute “biochar” consistent trends:
  • Highly variable and different responses to biochar as a function of soil ecosystem (microbial linkage), plant, & position on black carbon continuum:

What is clear – Biochar could be a piece of the solution

Just as the climate issues did not arise from a single source; the solution to the problem will not be a single solution

Soil C sequestration can be one piece of the solution

Multiple avenues should be utilized
Acknowledgements

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• Minnesota Biomass Exchange
• NC Farm Center for Innovation and Sustainability
• National Council for Air and Stream Improvement (NCASI)
• Illinois Sustainable Technology Center (ISTC) [Univ. of Illinois]
• Biochar Brokers
• Chip Energy
• AECOM
• Penn State
• University of Bonn (Germany)
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"The nation that destroys its soil destroys itself.” -- Franklin D. Roosevelt