The role of biochar in a negative emissions portfolio

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Biochar: An intervention in the terrestrial carbon cycle

Anthropogenic emissions: 8 Pg C yr⁻¹

Terrestrial NPP: 60 Pg C yr⁻¹

Heterotrophic respiration: (60 - X) Pg C yr⁻¹

Biochar: X Pg C yr⁻¹
Biochar consists of both labile (short-lived) and recalcitrant (long-lived) components.

Biochar stability depends primarily on (1) the labile fraction & (2) $T_{1/2}$ of recalcitrant fraction.

Centennial avoided emissions insensitive to $T_{1/2} > 200$ yrs.

Centennial avoided emissions are sharply reduced for $T_{1/2} < 100$ yrs.

Increasing soil BC stocks give rise to increasing soil CO$_2$ emissions from BC decomposition.

Eventually, “peak biochar” occurs when losses $\approx$ additions.

Long-term biochar sequestration requires high biochar stability ($T_{1/2} \approx 500$ yrs over 500 yr timescale).
Biomass conversion to biochar fundamentally changes the chemistry of organic matter.
Both decomposition and condensation reactions occur.

Increasing temperature:
- reduces H & O content
- increases aromaticity
- increases condensation of biochar (increased size of conjugated aromatic sheets)
- increases 3D order
- increases porosity & surface area
- increases pH & CEC
Biochar stability increases with pyrolysis temperature

- Estimates of biochar $\frac{1}{2}$ life span 6 orders of magnitude ($10^1 - 10^7$ yrs)
- $T_{\frac{1}{2}}$ corellates with O:C ratio
- Lower O:C $\Rightarrow$ higher $T_{\frac{1}{2}}$
- O:C reduced by
  - higher pyrolysis temperature
  - longer reaction time
- Feedstock also contributes to stability
  - Manure biochar least stable
  - Grasses less stable
  - Wood most stable
- $T_{\frac{1}{2}} > 1000$ yrs can be achieved by use of slow pyrolysis at $>500^\circ$C

(Spokas, 2011)
Global Distribution of soil BC

- BC is ubiquitous in global soils
- BC% of SOC peaks at 20-30° latitude (arid zone & regions with pronounced dry season)
- High BC% generally associated with most fertile soils (anthrosols, mollisols, chernozems)

(Krull et al., 2008)
**Effect on crop yields**

- **Anthropogenic Dark Earths in Amazonia, West Africa & Borneo highly fertile relative to adjacent soils**
  - ADEs built gradually over many decades/centuries.
  - Also contain raised non-pyrogenic SOC
  - Higher pH, Ca, n, P, K, Ca and water holding capacity
  - High P content possibly due to addition of bones or reduced leaching
  - May not be possible to replicate in short time scale

- Short-term field & pot trials have typically shown a 5-40% increase in yield

- **Mechanisms include:**
  - reducing pH constraints
  - lowering Al toxicity
  - Increased CEC
  - Sorption of anionic nutrients (nitrate, phosphate)
  - Increased water retention
  - Synergies with mycorrhizae

- **Yields can also be suppressed by**
  - raising pH on neutral/alkaline soils
  - N immobilisation from high labile-content biochar
  - lowering water retention in clayey soils

- **Different biochars need to be tailored to local soil constraints**

- **Long-term field trials still required.**
Yield improvements most pronounced on degraded or infertile (low CEC, low OM, sandy or nutrient constrained) soils.

Highly fertile soils typically do not show any improvement in yields.

Site-specificity is a common feature of all types of organic amendment.

Yield generally shows a strong synergistic positive interaction with mineral & organic fertilisers.
Biochar yield falls with temperature, but...
- C yield falls less strongly
- Fixed-C yield has little temperature response for $T > 400^\circ$C
- C-sequestration fairly independent of pyrolysis temp.
- Pyrolysis conditions should be optimised for energy production, economics, and emissions.
Coproduction of Energy with Biochar

- Per unit feedstock, increased biochar production implies reduced energy production.
- Initial biomass (dry, ash-free) has ~19 GJ Mg⁻¹
  - approx 7–8 GJ remains in biochar (slow pyrolysis)
  - Once losses accounted for, up to ~7 GJ energy available
- Several pathways to produce liquid & gaseous fuels or electricity
Biochar can be produced sustainably or unsustainably

Feedstock source of prime importance (as with all biomass technologies)

Pyrolysis emissions and energy production also important

Sustainability criteria:
- Agricultural & forestry residues procured at a rate that does not cause soil erosion or degradation or reduce food security
- Little C debt from land-use change or long-lived feedstocks
- No loss of habitat or biodiversity from direct or indirect land conversion
- No contaminated wastes used
- Low-emissions conversion technology
- Energy co-production
Avoided emissions attributions

- Main contribution due to sequestered C & fossil-fuel offsets
- Significant avoided CH₄ from paddy rice production
- Avoided N₂O accounts for 9% of mitigation impact
- Main negative impacts are BC decomposition and SOC loss
- Tillage & transport losses negligible
- Avoided emissions from bioenergy slightly larger than C-sequestration effect alone of biochar: greater benefit of biochar requires coproduction of energy
Relative mitigation potential of biochar and bioenergy (combustion) depends strongly on fossil fuel that is offset and local soil fertility
⊗ indicates baseline C-intensity and global-mean cropland soil-fertility
Least fertile soils yield greater benefit from biochar than bioenergy
Relative benefit of biochar increases as C intensity decreases
Contours steepest for biomass crops
Highest relative benefit (>80%) for poorest soils growing biomass crops offsetting low C-intensity fuels
Lowest relative benefit (-19%) for most fertile soil growing biomass crops and offsetting coal
Relative benefits of biochar and bioenergy depend highly on local conditions!
So far, comparison has only been on a per unit biomass basis. But…
Biochar affects (primes) turnover rates of non-pyrologic SOC
- Both increased initial respiration rates (+ve priming) and increased stabilisation (-ve priming) have been observed
- In the long term, stabilisation effects dominate
- Biochar may significantly increase npSOC
- SOC depletion is the limiting factor in sustainable biomass residue harvesting
1 ha of corn

Total crop residues per ha

Maximum sustainably harvestable crop residues

Biochar / bioenergy conversion

144 GJ (8 Mg)

36 GJ (2 Mg)

Liquid biofuel

29 GJ

Ethanol

32 GJ

Biochar

45 GJ (1.4 Mg)

Biochar returned to soil maintains / improves soil function and builds soil carbon
Economic effects of C Credits & fertility

- Payback period of 25 years or more
- Net profitability of biochar depends heavily on crop value enhancements
- Most cost effective on moderate fertility soils where total yield responses are highest
- Least fertile soils that benefit most from biochar are constrained by lower economic return and by lower feedstock availability
- No payback on highly fertile soil
- C credits have essentially no impact on relative profitability of biochar and bioenergy

Figures courtesy of J. Amonette, Pacific Northwest National Laboratory
Cost of biochar production varies considerably with feedstock (-£200 to +£390 Mg\(^{-1}\) for large-scale biochar systems in the UK)

- Biochar from waste products for which ‘tipping fees’ paid may have negative production cost
- Feedstock cost is largest component of production cost

(Shackley et al. 2010)

6x10\(^6\) Mg CO\(_2\) yr\(^{-1}\) abatement potential for < £20 Mg\(^{-1}\)
Global cost curve for GHG abatement

Source: Enkvist et al. (2007)

- €21-30 per tCO$_2$e (from McCarl 2009)
- 3.7-6.6 GtCO$_2$e/yr abatement (Woolf et al. 2010)
Summary & Conclusions

- Biochar can be engineered to be sufficiently stable to sequester C for several centuries.
- Short term field & pot trials typically show improved yields in poor soils.
- Fertile soils typically show no improvement in yield (although water and fertiliser inputs and runoff may be reduced).
- No long-term field-trial data are available, although BC-rich soils often have high fertility.
- Climate mitigation potential of biochar is greater than bioenergy except where fertile soils coexist with high C-intensity energy supply.
- Short-term economics favour bioenergy over biochar; long-term favours biochar.
- Payback times before biochar is more economic than bioenergy range from 25-70 yrs (shortest on soils with moderate fertility constraints).
- If applied equally, C credits have little impact on relative economics of biochar and bioenergy.
- A more comprehensive comparative-analysis of the uses of biomass for GHG-mitigation is required, looking at a wide range of options (co-firing, AD, burial, biochar, biofuels, electricity, BECCS...) for an array of potential feedstocks and geographic locations.
- Comparisons between uses of biomass must consider not just economics, energy and GHGs, but also wider issues including soil conservation, biodiversity, hydrology & nutrient cycling.
References

- Lehman et al. (2011) Role of biochar in mitigation of climate change, Imperial College Press
Crop Value—Maize: $300/Mg
Yield increase builds with additional biochar amendments
Biomass Amount: 1 Mg C/yr; biochar from this applied to 1 ha annually.
Fossil Fuel Carbon Intensity: 17.5 KgC/GJ
Energy Value: $3.00/GJ
Cost of Production/Transportation:
- $70/ MgC slow pyrolysis
- $50/ MgC combustion
C Credits: $0-$200/Mg C
Soil Fertility Response Factor: 0-1
Time: 0-100 years
On average, biochar has higher mitigation potential than bioenergy except when in most C-intense economies (e.g. where coal is only fuel)

Sensitivity to C intensity is lower than bioenergy

In low carbon-intensity location or future, biochar maintains significant GHG reductions