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monica.mccall@imperial.ac.uk

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Multi-method assessment of Biochar Permanence

Monica McCall, Jan Hennissen , Chris Vane, & Mark Sephton

Background

- Biochar is the largest durable carbon dioxide removal (CDR) market globally.[1] Permanence certification uses proxies that have yet to be compared against biological ground-truth
- Rock-Eval 6, which thermally separates biochar into pyrolysable (PC) and recalcitrant (RC) fractions, is an emerging technique to quantify reactive and stable carbon, respectively[2]
- Reflectance Microscopy quantifies the degree of carbonisation. A mean reflectance value (R_0) > 2.0% is a threshold for geologically inert carbon, linking organic petrography to permanence assessment[3]
- Both methods are gaining momentum in biochar analysis, but neither has been validated against biological mineralisation data across biochar feedstock and pyrolysis temperature
- Short-term incubation of soil and biochar captures the biologically labile carbon pool (C_{labile}), which is mineralised as CO_2 within months[4]

Research Question

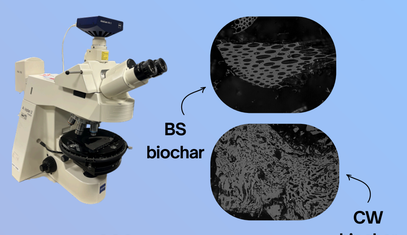
Do organic petrographic metrics and biological incubations of biochar agree with each other?

Methods

Biochar production

Chestnut Wood (CW) & Barley Straw (BS)
Pyrolysis: 400-700 °C

Reflectance Microscopy

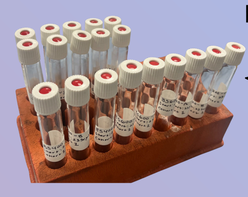


200 measurements per sample

Rock-Eval 6 pyrolysis

Key outputs
Pyrosylsable C (PC %)
Recalcitrant C (RC%)
Total Organic C (TOC%)
$T_{pk}S2$ (°C)
Hydrogen Index (HI)
Oxygen Index (OI)

Biological Incubation



32 °C for 6 months

two-pool decay model

decays rapidly → C_{Labile}; recalcitrant → C_{Stable}

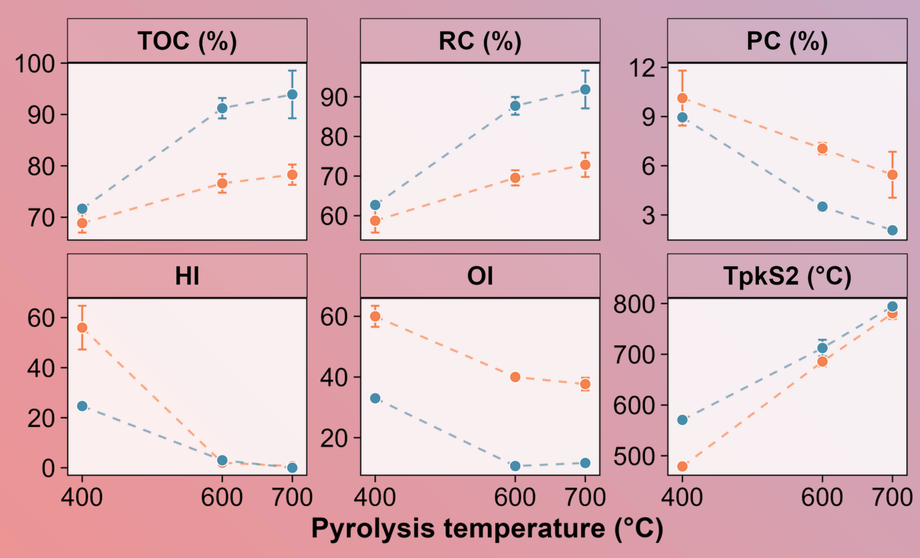
$$C_t = C_{Labile}(1 - e^{(-K1t)}) + C_{Stable}(1 - e^{(-K2t)})$$

C(t) = cumulative CO_2 mineralised at time t, K = decay rate

Results

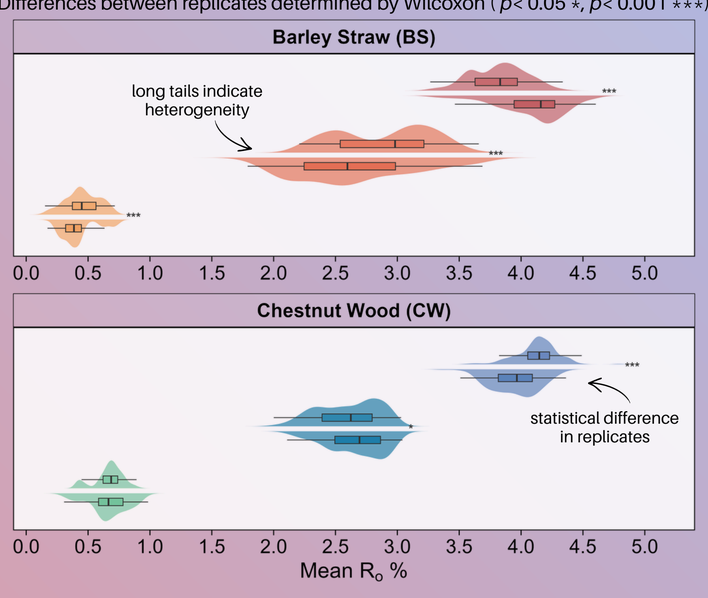
1 Rock-Eval 6 Pyrolysis Outputs

Points = group mean ± 1 SD (n = 3). TOC = total organic carbon, RC = recalcitrant carbon, PC = pyrolysable carbon, HI = hydrogen index, OI = oxygen index, TpkS2 = max temperature at hyrdocarbon release peak



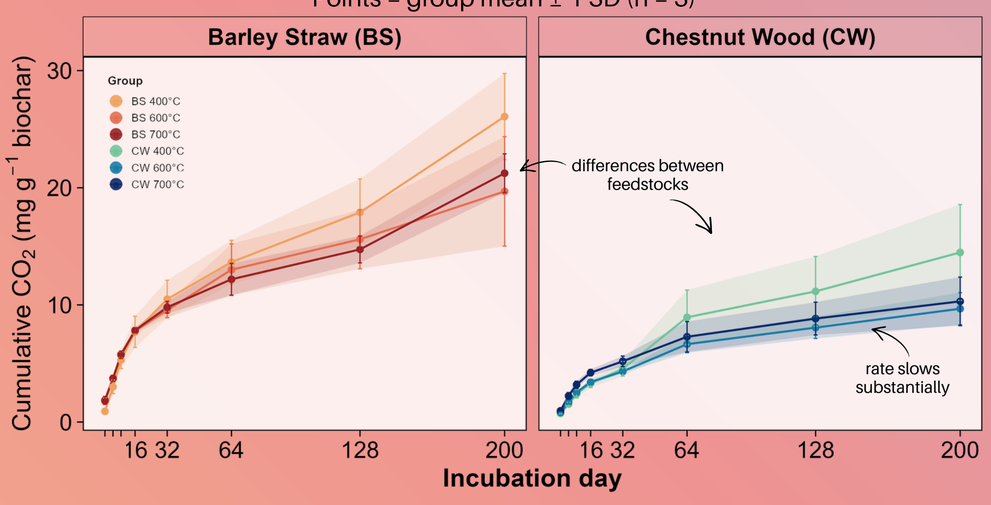
2 Reflectance Microscopy Mean R_o values

Differences between replicates determined by Wilcoxon ($p < 0.05$ *, $p < 0.001$ ***)

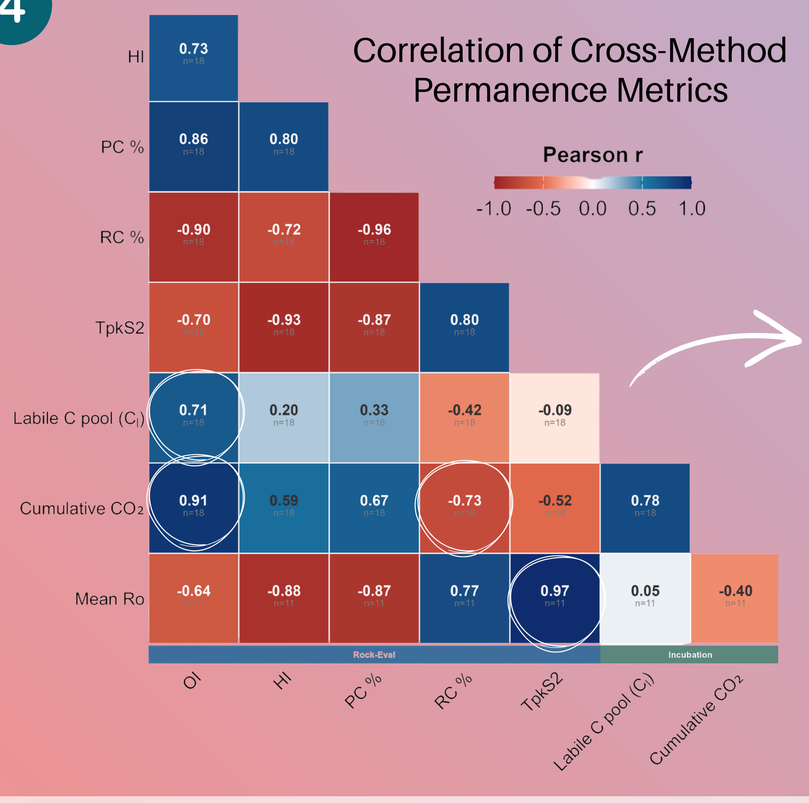


3 Biological Incubation Carbon Mineralisation

Points = group mean ± 1 SD (n = 3)



4 Correlation of Cross-Method Permanence Metrics



- Intra-method metrics generally correlate well, confirming internal consistency across methods
- Strongest correlation was between Mean R_0 and $T_{pk}S_2$ (r = 0.97)
- Cumulative CO_2 correlated positively with OI and negatively with RC%
- Modelled labile C pool values correlated best with OI, but only weakly with other metrics

Conclusions

- Both feedstock and temperature impact biological mineralisation rate and Rock-Eval permanence metrics, but feedstock did not have an effect on R_o values
- Reflectance microscopy and Rock-Eval share strong cross-method correlations: Mean R_0 and $TpkS_2$ achieve r = 0.97, validating both as complementary thermal maturity indicators
- Rock-Eval OI & RC% reflect biological reactivity and recalcitrance respectively, supporting their use in carbon crediting
- Modelled labile C pool showed weaker cross-method correlations than observed cumulative CO_2, which is a more direct empirical measure of biological carbon loss
- Thermochemical proxies for labile and stable carbon pools are analogous to C_{Labile} and C_{Stable} in the biological decay model, though results indicate that thermal and biological reactivity are not strictly equivalent.

References:

1. Biochar's Market Leadership in Carbon Removal. Website (Puro.earth) https://puro.earth/our-blog/346-biochars-market-leadership-in-carbon-removal (2025).
2. Behar, F., Beaumont, V. & De B. Penteado, H. L. Rock-Eval 6 Technology: Performances and Developments. Oil & Gas Science and Technology - Rev. IFP 56, 111–134 (2001).
3. Sanei, H. et al. Quantifying inertinite carbon in biochar. International Journal of Coal Geology 310, 104886 (2025).
4. Wang, J., Xiong, Z. & Kuzyakov, Y. Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8, 512–523 (2016).