APPENDIX 1 (Accompanying Chapter 4 - Impacts of biochar on soil - Saran Sohi)

Analysis of scientific studies published on the function of char, its quantification, and its stability in soil

See References in the main report for full citations and the Glossary for abbreviations. Additional notes accompany table beneath the last row

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Ref no.	Source	Research parameters			Char		Design				Findings	Pyrolysis & char					Experimental parameters						Soils				
		Context	Topic(s)	Type of study	Feedstock	Type	Duration (d)	Time-points	Factors	Variables		Peak temp (C)	Duration (h)	Oxygen restriction	Char pH	Char particle size (mm)	Medium	Char addition rate*	Scale	plants	Temperature(s) Category	Temperature(s) Range (C)	Land-use(s)	No.	Texture Categ-ory	Texture Clay range (%)	pH
1	Asai et al., 2009	Soil fertility	Crop yield	Dynamic	Wood	Charcoal	140	1	Fertiliser nitrogen rate; tillage; soil type	Crop yield; leaf greenness; soil hydraulic conductivity	Char increased soil water conductivity and crop phosphorus uptake, but reduced crop nitrogen response and leaf green-ness	n/s	n/s	Limited	7.5	0-2	Soil + char	Medium; High	Field	Yes	n/s	n/s	Arable	10	Range	26-48	5.2-8.3
2	Ascough et al., 2009	Quantification	HyPy for black carbon isolation	Static	n/s	Archaeological	Archaeological	1	HyPy temperature; soil type	^{14}C dating; hydrogen pyrolysis	HyPy purifies black carbon in diverse samples	n/a	n/a	n/a	n/a	n/a	Char only; soil only	n/a	Lab	No	n/s	n/s	n/s	3	Range	24-70	n/s
3	Baldock and Smernik, 2002	Stability	Biological oxidation	Static	Wood	Synthetic environmental charcoal	120	0	Pyrolysis temperature; carbon substrate	SOC; carbon NMR; Infra-red spectroscopy	<2% char C lost for formation 250-350 degrees, below 200 degrees x10 more mineralisation	70-350	24-72	Partial	n/s	n/s	Sand	Very high	Lab	No	Tropical	25	n/a	1	Sand	0	6.3
4	Beaton et al., 1960	Soil fertility	phosphorus sorption	Static	Wood	Environmental charcoal; Synthetic environmental charcoal	n/s	n/s	Pyrolysis temperature; ambient temperature	Phosphorus adsorption	Ortho-phosphorus adsorbed to charcoal specifically probably via hydrogen bonds	n/s	n/s	n/s	n/s	n/s	Char in solution	n/a	Lab	No	Tropical	20-45	n/a	n/a	n/a	n/a	n/a
5	Bird et al., 2008	Soil physical effects	Porosity	Static	Wood	Synthetic environmental charcoal	0	0	Pyrolysis temperature	Pore size; pore neck diameter	Oxygen in pyrolysis and post-pyrolysis oxidation increases pores and pore connectivity in char; surfaces for association with clay minerals	300, 600	1-2	0, 98%	n/s	7	Char only; peat + char	n/a	Lab	No	n/a	n/a	n/a	n/a	n/a	n/a	n/a
6	*Blackwell et al., 2007*	Soil fertility	Crop yield	Dynamic	Short rotation coppice	Charcoal	180	1	Char addition rate	Crop yield; mychorrhizal fungi, plant growth, soil nutrients, pH	Large impact of mycorrhizal fungi gives estimated economic gain of USD 100 ha^{-1}	n/s	n/s	Limited	8.4	2-3	Soil + char	Medium; High	Field	Yes	n/s	n/s	Arable	3	n/s	5-20	5.3
7	Brodowski et al., 2005a	Surface reactions	Oxidation	Static	Atmosphere soot	Environmental charcoal	n/a	0	Spectroscopy methods	Carbon NMR; EDX; SEM; O-to-C ratio; atomic force microscopy	Density and size of particle control chemisorbed O:C at surface, mineral protection	300	2	Restricted	n/s	n/s	Soil + char	n/a	Field	Yes	Temperate	n/s	Arable	1	n/s	n/s	n/s
8	Brodowski et al., 2006	Stability	Aggregation	Static	Wood	Environmental charcoal	n/s	1	Land-use; tillage	Soil physical fractions; BPCA	Relative enrichment of higher density occluded fraction with black carbon	n/s	n/s	n/s	n/s	n/s	Soil + char	n/a	Field	Yes	Temperate	8	Arable	1	n/s	17	n/s
9	Brodowski et al., 2007	Quantification	Stability	Static	Atmosphere soot	Black carbon	n/s	1	Soil type; tillage; fertiliser nitrogen	BPCA biomarker; soil physical fractions	No effect of 30 y of fertiliser or tillage on black carbon, 30% is from fire, black carbon in silt size fraction or smaller	n/s	n/s	n/s	n/s	n/s	Soil + black carbon	n/a	Field	Yes	Temperate	9	Arable	3	Range - silty	n/s	5.6-7.6
10	Bruun et al., 2008	Stability	Char fractions	Dynamic	Cereal straw	Synthetic environmental charcoal	113	15	Pyrolysis temperature	$^{14}CO_2$; soil microbial biomass ^{14}C	Labile char fraction is less than 10% of total carbon when formed at higher temp., <2% at lower temp., proposes CaCO3 formation during pyrolysis	225-375	24	Restricted	n/s	n/s	Soil + char	Very high	Lab	No	Tropical	25	Arable	1	Sandy loam	13	n/s
11	Bucheli et al., 2004	Contaminants content	PAH	Static	n/s	Black carbon	0	0	Land-use; location	Black carbon (CTO), PAH (EPA 16)	0.05-0.6 mg/kg PAH, about <0.1% of low BC contents measured by CTO - soils typically 0.4-1.8 mg/kg	n/a	n/a	n/a	n/a	n/a	Soil + black carbon	n/a	Field	Yes	Temperate	0-11	Agricultural; Forest	23	Range	n/s	4.0-7.2
12	Campbell et al., 2008	Microbial impacts	Microbial activity	Static	Wood	Environmental charcoal	Long-term (33 yrs)	1	Fire frequency	Substrate induced respiration; microbial diversity (biolog, PLFA)	Fire has an effect on substrate induced respiration and char concentrations in soil	n/s	n/s	n/s	n/s	n/s	Soil + char	n/a	Field	Yes	n/s	n/s	Forest	1	n/s	n/s	n/s
13	Chan et al., 2007	Soil fertility	Nitrogen use	Static	Green waste	Slow pyrolysis char	42	0	Char addition rate; fertiliser nitrogen	Crop yield; soil pH; soil CEC; soil strength; water holding capacity	Yield effects in combination with N fertiliser (only); increase pH and field capacity, decrease in tensile strength at high char rate	450	n/s	Total	9.4	n/s	Soil + char	Medium; high; very high	Glasshouse	Yes	n/a	20-26	Arable	1	n/s	n/s	4.5
14	Chan et al., 2008	Soil fertility	Crop yield	Dynamic	Poultry manure	Slow pyrolysis char	42	1	Char addition rate; fertiliser nitrogen; pyrolysis temperature	Crop yield; soil microbial biomass; earthworm avoidance	Char resulted in higher yield and crop N uptake; positive effect on earthworm conc.	450,550	n/s	Total	9.9, 13	n/s	Soil + char	Very high	Pots	Yes	n/a	20-26	Arable	1	n/s	n/s	4.5
15	Cheng et al., 2006	Stability	Abiotic vs. Biological oxidation	Dynamic	Wood	Synthetic environmental charcoal	120	1	Temperature; manure and fertiliser nitrogen; microbial inoculation	CEC; X-ray photo-electron spectroscopy; pH; carbon NMR; infra-red spectroscopy; O-to-C ratio	Evident surface oxidation primarily abiotic irrespective of soil and innoculum used	350	5.4	Limited	16	0-2	Char only; soil + char, char + manure	Very high	Jars	No	n/a	30,70	Grazed grass	1	n/s	n/s	4.3
16	Cheng et al., 2008a	Stability	Oxidation	Static	Wood	Environmental charcoal	110	1	Temperature; time	Soil respiration; X-ray photo-electron spectroscopy; infra-red spectroscopy; CEC; O-to-C ratio	Climate oxidation effect > biological and not limited by quality; x7 at char surface	n/s	n/s	Restricted	n/s	n/s	Char only	n/s	Field	Yes	Temperate range	3.9-15.7	Forest; agricultural grassland	11	n/s	8-54	4.5-7.2
17	Cheng et al., 2008b	Stability	Age	Dynamic	Wood	environmental charcoal	Long term (137 y)	5-13	Soil origin, soil depth; char age and origin	Soil CO_2; char CO_2; char turnover rate	No effect of soil origin on ratio of stable and labile char fractions, modelled mean residence time, labile 19d, stable 59 y in lab	n/k	n/k	n/k	n/s	1-2	Char only, soil + char	n/k	Jars	no	Temperate range	3.9-17.2	Forest; agricultural grassland	16 (7)	n/s	19-42	3.8-6.7 (3.8-5.3)
18	Clough and Skjemstad, 2000	Quantification	Carbon-NMR spectroscopy	Static	n/k	Environmental charcoal	n/a	n/a	Soil texture; soil carbonate content	Carbon NMR; UV oxidation	High char content 17-40% indicated by aryl NMR peak after photo oxidation	n/k	n/k	n/k	n/s	n/s	natural soil + char	n/k	n/a	no	n/s	n/s	Agricultural	7	n/a	19-42	7.7-8.3
19	Czimczik et al., 2002	Composition	NMR spectroscopy	Static	Wood rot	Slow pyrolysis char	0	0	Pyrolysis temperature	Mass; ^{13}C isotope; carbon NMR; carbon	Decrease in ^{13}C with pyrolysis	340, 480	15	Total (inert gas)	n/a	n/a	char	n/a	n/a	No	n/a	n/a	n/a	n/a	n/a	n/a	n/a
20	Dai et al., 2005	Quantification	Stability	Static	Grass	Environmental charcoal	0	0	Soil depth; burning	BPCA biomarkers	Net addition from individual fire not measurable; rel. enrichment with depth. 5-13% of SOC	n/k	n/k	Partial	n/s	n/s	Soil + char	n/k	Field	Yes	Temperate	n/s	Agricultural grassland	1	n/s	n/s	n/s
21	Das et al., 2008	Soil fertility	Pyrolysis fractions	Dynamic	Wood: poultry manure	Synthetic environmental charcoal	120	1	Pyrolysis process; pyrolysis fractions	CO_2; O_2; trace gases	Aqueous fraction of pyrolysis liquids are degradable	500	0.1	Total (N_2)	n/s	n/s	Soil + char; water + char	Medium	Lab	No	high	37	n/s	1	n/s	n/s	n/s
22	Fernandes et al., 2003	Stability	Solvent extractable fractions	Static	Wood, cereal straw, BC	Synthetic charcoal, charcoal, soot	0	0	Char type	Specific surface area (BET); elemental C, H & N; solvent-extractable organic matter; carbon NMR; polar / non-polar organic compounds	Solvent-extractable organic matter low in charcoal (high in soot, clogs pores and surfaces)	450	1	Limited	n/s	n/s	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
23	Gaskin et al., 2007	Soil fertility	Water dynamics	Dynamic	Wood, nutshells	Synthetic environmental charcoal	180	*1*	Char addition rate; pyrolysis temperature; temperature; feedstock	Crop yield; water retention curve; Cation exchange capacity, ash	Suggests an effect of char on water retention curves but not significant; CEC 14-44 cmol kg-1	380-420	n/s	Total	n/s	n/s	Soil + char	Medium; high	Plots	Yes	n/a	n/a	Arable	1	Loamy sand	n/a	n/a

24	Glaser et al., 2000	Soil organic matter	Priming, vertical transport	Static	Wood	Charcoal	Archaeological	0	Soil type; soil depth; Char addition rate	EDX; soil physical fractions; BPCA biomarker; scanning electron microscopy	Char invisible to SEM & EDX suggests mineral complexation of >50%	n/k	n/k	*Limited*	n/s	n/s	Soil + char	n/k	field	Yes	Tropical	n/s	Agriculture, forest	4	Sand-clay	n/s	3.9-5.5
25	Guggenberger et al., 2008	Stability	Mobility, biomarkers	Static	Wood	Environmental charcoal	0	0	Landscape position	BPCA biomarker, DOC	Char comprises less than 3% of SOC in tundra, about 30tC.ha-1, with trivial erosion rates	n/k	n/k	*Partial*	n/s	n/s	Soil + char	n/k	Field	Yes	Cold	-7.4	Natural tundra grassland	3	Silty	n/s	n/s
26	Hamer et al., 2004	Stability	Priming	Dynamic	Grass, straw, wood	Synthetic environmental charcoal	26, 34	13	Pyrolysis temperature; substrate; pH	Substrate induced respiration; carbon NMR; ^{14}C; elemental analysis of O, C, H, S, P	99.75% of wood char stable at 60d; priming (x2) by glucose least in wood; glucose primed	350, 800	1-22	Limited	n/s	Milled	Sterile sand + char	Extreme	Jars	No	Tropical	20	Arable	1	Sand	n/a	6.5
27	Hammes et al., 2007	Quantification	method comparison	Static	Grass, wood, BC	Synthetic, environmental, soot, shale, coal, pigment	0	0	Char type (matrix), analytical method	Thermal and/or chemical oxidation; BPCA biomarker; photo-oxidation; calorimetry	Thermal approach is optimal, showing consistency in char from wood to grass (80% and 30% in SOC)	450	5	Total	n/s	n/s	Char only; soil + char	n/a	n/a	No	n/a	n/a	n/a	n/a	n/a	n/a	n/a
28	Hammes et al., 2008	Quantification	Black carbon; Mean residence	Static	Various	various	0	0	Char type, analytical method, matrix	Phosphorus NMR; carbon NMR; specific surface area; soil colour; H-to-C ratio; C-to-O ratio	Elemental H:C and C:O ratios provide best universal measures and predictors of char dynamics	n/s	n/s	Various	n/s	n/s	Char only; soil + char	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
29	Hockaday et al., 2006	Stability	Mobility, biomarkers	Static	Wood	Environmental charcoal	Long-term (87 y)	1	Soil with char / no char	Scanning electron microscopy; Dissolved organic matter; FTICR	0.2% of aged natural charcoal-C extractable in water; high double bond equivalents	n/k	n/k	*Partial*	n/s	>2	Char only	n/k	Field	Yes	Temperate	6.7	Forest	1	Sandy	n/a	4.4
30	Janik et al., 2007	Quantification	Mid infra-red spectroscopy	Static	*Wood*	Environmental charcoal	n/k	1	Location / origin	Mid-infra red spectroscopy; SOC; char; particulate organic carbon	Can estimate char independent of SOC - may not be transferable between sites	n/k	n/k	*Partial*	n/s	n/s	Soil + char	n/k	Field	Yes	Warm temperate	n/s	Various	177	n/a	0-80	n/s
31	Kaal et al., 2007	Quantification	Molecular mixing models	Static	*Wood*	Environmental charcoal	Long-term (5000 year)	1	Soil depth	NMR groups; pyrolysis GC mass spec. functional groups	Some comparability between methods, enhanced by molecular mixing model	n/k	n/k	*Partial*	n/s	n/s	Sterile sand + char; water + char	n/k	Field	Yes	Temperate	9	peat	1	n/a	n/a	3.5-4.6
32	Kaal et al., 2008a	Stability	Mobility, biomarkers	Static	Wood	Environmental charcoal	Long-term (700-7200)	1	Soil depth	NMR, pyrolysis GC mass spec., biomarkers (incl. PAH)	Charcoal <1% SOC; NMR and analytical pyrolysis yield broadly consistent information on composition	n/k	n/k	*Partial*	n/s	>2	Soil + char	n/k	Field	Yes	Temperate	15	n/s	1	n/s	n/s	4.7-5.1
33	Kaal et al., 2008b	Stability	Mobility, biomarkers	Static	Wood	Environmental charcoal	Long-term (8500)	1	Soil depth	NaOH fraction, pyrolysis GC mass spec., functional groups, biomarkers (incl. PAH)	Stable molecules apparent in char, PAH high in DOM, levoglucosoan a characteristic marker	n/k	n/k	*Partial*	n/s	>2	Soil + char	n/k	Field	Yes	Temperate	15	n/s	28	n/s	n/s	5.0
34	Kimetu, 2008	Soil organic matter	Priming	Chronosequence	Wood	Charcoal	Long-term (36500)	5	SOC, Soil texture, organic soil amendment	Soil pH, soil nutrients	Organic matter accumulation with char applied to low-SOC soils	400-500	n/s	Restricted	9.4	1-20	Soil	Medium	Field	Yes	Sub-tropical	19	Arable	15	Fine	13, 47	5.2-6.3
35	Knicker and Skjemstad, 2000	Quantification	Nitrogen-NMR spectroscopy	Static	n/k	Environmental charcoal	0	0	Soil type	Nitrogen and carbon NMR; hydrofluoric acid demineralisation; UV oxidation	Pyrrolic N major component of protected SOM nitrogen in char	n/k	n/k	n/k	n/k	n/k	Soil + char	n/a	n/a	n/a	n/a	n/a	n/a	5	n/s	47-70	5.7-8
36	Knicker et al., 2007	Quantification	Mean residence	Static	Grass, pure	Environmental charcoal	30-730	0	Potassium dichromate oxidation, oxidation time	Char residual mass, carbon NMR, nitrogen NMR	Oxidisable char 40-80% to 18-60% over time - and non-graphitic, potassium dichromate method underestimates soil charcoal	n/a	n/a	*Partial*	n/a	n/a	Soil + char	n/a	Field	Yes	n/s	n/s	n/s	7	Sandy loam, clayey loam	10-40	n/s
37	Knicker et al., 2007	Quantification	Chemical; oxidation	Static	Grass, wood	Synthetic environmental charcoal	0	0	Potassium dichromate oxidation, oxidation time	Char residual mass, carbon NMR, nitrogen NMR	Oxidisable char 40-80% to 18-60% over time - and non-graphitic, potassium dichromate method underestimates soil charcoal	350	0.07-0.2	Limited	n/s	n/s	Char	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
38	Knicker et al., 2008	Stability	Composition, range	Static	Wood, grass, pure compounds	Synthetic environmental charcoal, charcoal	0	0	Pyrolysis temperature	Carbon NMR, elemental analysis	Char is not graphitic in structure	350	0.13	Partial	n/s	n/s	Char	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
39	Krull et al., 2003	Stability	Natural abundance isotope tracing	Static	Wood, grass	Synthetic environmental charcoal; Environmental charcoal	0	0	Pyrolysis temperature	^{13}C enrichment; Pyrolysis GC mass spec., carbon NMR	Isotopic fractionation occurs only in occluded feedstock	250-860	0.3-2.0	Partial	n/s	n/s	Char	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
40	Kuo et al., 2008	Quantification	Biomarkers, MRT	Static	Wood, grass	Synthetic environmental charcoal	0	0	Time; temperature; pyrolysis temperature	Biomarkers (levoglucosan), elemental N, C, H, O, ash, potassium dichromate oxidation	Charcoal is heterogeneous levoglucosan is too sensitive to charring conditions to provide a marker for total char in soil	150-1050	0.5-5.0	Limited	n/s	n/s	Char	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
41	Kuzyakov et al., 2009	Stability	Priming	Dynamic	Grass	Synthetic environmental charcoal	1181	44	Substrate; tillage; SOC	$^{14}C\ CO_2$	Short-term priming of biochar decomposition by glucose, but assuming 10% lab rates MRT is millennial	200-400	3-13	Limited	n/s	n/s	Soil + char	Medium	Jars	No	Temperate	20	Agricultural	2	n/s	23	6.0
42	Lehmann et al., 2003	Soil fertility	Nutrient dynamics	Dynamic	Wood	Charcoal	45	1	Pre-existing soil charcoal, char addition rate; char particle size; pyrolysis temperature	Crop yield, crop nutrients, soil nutrients, root and shoot biomass	Char enriched soil: high soil N with zero leaching; other nutrients highly available; Soil + char: N immobilisation	n/s	n/s	Limited	n/s	1,10	Soil + char	Very high; Extreme	Glasshouse	Yes	Tropical	n/s	Forest	2	n/s	65,5	5.1, 5.7
43	Lehmann et al., 2003	Soil fertility	Char leaching	Dynamic	Wood	Charcoal	37	15	Char addition rate; char particle size; fertiliser rate, manure + nitrogen; pyrolysis temperature	Crop nutrient uptake; leached charcoal nitrogen	Char enriched soils: no leaching except with fertiliser addition; Soil + char mitigates N leaching	n/s	n/s	Limited	n/s	1,10	Soil + char	Very high; Extreme	Glasshouse	Yes	Tropical	n/s	Fallow	2	n/s	65,5	5.1, 5.7
44	Lehmann et al., 2005	Stability	Surface oxidation	Static	*Wood*	Environmental charcoal	Long-term (6000 y)	2	Age	Near-edge X-ray absorption spectroscopy	Surface oxidation of char, aromatic core maintained over time	n/k	n/k	*Limited*	n/s	0.005-0.08	Char only	n/k	Field	Yes	Tropical	26	Forest	2	n/s	n/s	n/s
45	Leifeld, 2008	Soil fertility	Indirect effects; fertiliser use efficiency	Static	n/k	Environmental charcoal	0	0	Soil / location	^{14}C age, SOC	Char affects ^{14}C-age estimates for SOC and hence turnover rates assume in SOC modelling	n/k	n/k	*Limited*	n/a	n/a	Soil + char	Low; Medium	Field	Yes	Cool temperate	9	Agricultural grassland	2	n/s	17,44	n/s
46	Liang et al., 2006	Stability	Surface interactions	Static	*Wood*	Charcoal	Long-term (800-7700 y)	0	Char addition rate	CEC; specific surface area; BPCA biomarker; near-edge X-ray absorption spectroscopy	CEC per SOC at equiv. pH enhanced by char, effect dependent on initial soil organic matter status	n/k	n/k	*Limited*	n/s	0.01	Char only	n/k	Field	Yes	Tropical	26	Forest	8	n/s	1-36	3.9-6.4
47	Liang et al., 2009a	Stability	Biological oxidation	Static	*Wood*	Charcoal	Long-term (5000 y)	14	Char age, char / no char	Near-edge X-ray absorption spectroscopy; X-ray photo-electron spectroscopy; soil physical fractions, basal soil respiration	Oxidation affects only char surfaces, not MRT of remaining char; no effect of soil texture or char age on carbon specific soil respiration; char-rich soils contain smaller labile and particulate carbon fractions	n/k	n/k	*Restricted*	n/k	n/k	Soil + char	n/k	Jars	Yes	High	30	Forest and agriculture	4	n/s	0-36	3.9-6.4
48	Liang et al., 2009b	Stability	Priming	Dynamic	Wood	Charcoal	532	6	Char type; soil type; substrate; char age	Substrate induced respiration; soil physical fractions; ^{13}C isotope; soil microbial biomass	Substrate induced respiration lower in *terra preta* where aged char is present; char sorbs lysed soil microbial biomass-C	n/k	n/k	*Restricted*	n/k	n/k	Soil + char	n/k	Jars	No	High	30	Forest	3	n/s	n/s	n/s
49	Major et al., 2009	Stability	Mobility, priming	Dynamic	Wood	Charcoal	730	27(6)	Char addition rate, soil depth	Soil respiration, DOC, particulate organic carbon, soil black carbon, crop biomass	Migration rate fro char in sub-soil 0.5-3%, 2% respired, 1% leached (preferentially). Plant productivity doubled, increasing soil respiration	400-600	48	Restricted	10.1	<0.9	Soil	Medium, high, extreme	Plots	Yes	Tropical	26	Grassland	1	Sandy clay loam	n/s	n/s

50	Michel et al., 2009	Quantification	Infra-red spectroscopy	Static	Wood, BC	Coal, charcoal	n/a	n/a	Char addition rate; SOC; soil extraction temperature	Mid-infra red spectroscopy, near infra-red spectroscopy	Method applicable to specific sets of soils	400	168	Limited	n/s	n/s	Soil only; soil + char	High; very high	Lab	No	n/a	n/a	n/a	n/a	n/a	n/a	n/a
51	Murage et al., 2007	Soil organic matter	Pool dynamics	Dynamic	Wood	Environmental charcoal	Long-term (63 y)	1	Tillage	Soil density fractions; ^{13}C isotope; Charcoal	Char reduces apparent turnover of free SOM - 2.5x faster without char. No tillage impacts on char stability	n/k	n/k	*Partial*	n/s	n/s	Soil + char	Medium	Field	Yes	n/s	n/s	Agricultural arable land	1	n/s	n/s	n/s
52	Nguyen et al., 2008	Quantification	Stability	Chronosequence	Wood	Environmental charcoal	Long-term (1000 y)	8	Char addition rate	O-to-C ratio; X-ray photo-electron spectroscopy; FTIR; carbon NMR	66% of char disappeared in 30 y, but no more thereafter	n/k	n/k	*Partial*	n/s	<0.03, >0.05	Soil + char	Medium	Field	Yes	Sub-tropical	19	Post-forest agriculture	9	n/s	45-49	n/s
53	Nguyen & Lehmann, 2009	Stability	Abiotic processes	Dynamic	Wood: cereal straw	Slow pyrolysis char	365	5	Temperature; water availability	O-to-C ratio; mass; Q10; pH; cation exchange capacity, FTIR	Abiotic char Q10 higher than Q10 of labile char; fluctuating water content accelerates decomposition	350, 600	2	Total	4.8-6.7	0.5-2.0	Sand + char	Very high	Lab	No	Tropical	30	n/a	2	Sandy	n/a	n/s
54	Oguntunde et al., 2004	Soil fertility	Crop yield, priming	Static	Wood	Charcoal	0	0	With and without char	Crop yield, soil texture, soil pH, soil nutrients	Grain yield doubled, increase biomass, large increase in soil potassium also pH and available phosphorus, difference in soil carbon not significant	n/k	n/k	*Restricted*	n/k	n/k	Soil	n/k	Plots	Yes	Tropical	n/s	Arable	12(4)	Sandy	6	5.8
55	Oguntunde et al., 2008	Soil physics	Water dynamics, radiative balance	Static	Wood	Charcoal	0	0	Char/no char	Soil heat capacity; soil porosity; soil albedo; soil bulk density; soil water infiltration	High soil charcoal contents at kiln sites has a drastic affect on soil physical and thermal properties	n/k	n/k	*Restricted*	n/s	n/s	Soil + char	Very high	Glasshouse	No	Tropical	n/s	n/s	12	n/s	3-11	n/s
56	Oros et al., 2002	Detection	erosive transport	Static	various	Vegetation	0	0	Soil type, burning	GC mass spec.; lipid extraction	Lipid markers sensitive to formation condition and volatilisation	n/k	n/k	Partial	n/s	n/s	Natural soil + char	n/k	Field	Yes	Temperate range	n/s	Grassland / forest	9	n/s	n/s	n/s
57	Pignatello et al., 2006	Soil organic matter	Sorption	Dynamic	Wood	Charcoal	14	1	Humic acids; organic compounds; temperature; treatment time	Adsorption; specific surface area	Temperature has an effect on blocking of charcoal micropores	340, 400	2	Minimal	n/s	<0.15	Solution + charcoal	High	Lab	No	n/a	20	n/a	n/a	n/a	n/a	n/a
58	Rhodes et al., 2008	Contaminant sorption	PAH	Dynamic	n/s	Activated charcoal	20	4	Addition rate; soil type; SOC	Sorption; $^{14}CO_2$; solvent extraction	Phenanthrene strongly sorbed by activated charcoal and rendered less biologically available	n/s	n/s	n/s	n/s	<0.02	Soil + char	Medium; high; very high	Jars	No	n/a	20	n/s	4	Loam, clay loam	18-42	5.4-7.5
59	Rogovska, 2009	Trace gas effects	N_2O	Dynamic	Wood	Slow pyrolysis char	497	n/a	Biochar addition rate, manure	CO_2, nitrous oxide, leached nitrogen, bulk density, soil pH	Increased CO_2 flux, decreased N_2O, increased pH (up to 1 unit), no biochar loss	n/s	n/s	*Total*	n/s	<0.5	Soil + char	Medium, high, very high	Tubes	No	n/a	22	n/s	1	Clay-loam	n/s	n/s
60	Rondon et al., 2007	Soil fertility	Biological N fixation	Dynamic	Wood	Synthetic environmental charcoal	75	1	Char addition rate	Biological nitrogen fixation; crop grain yield; crop biomass yield; nutrient uptake; mycorrhizal colonisation	Biological nitrogen fixation increased by nutrient effects of char up to 6% addition rate	350	1	Limited	7	0-2	Soil + char	Medium, high, very high, extreme	Glasshouse	Yes	Tropical	25	Arable	1	Clay-loam	n/s	5.0
61	Rumpel et al., 2007	Stability	Oxidation, morphology	Static	Wood	Environmental charcoal	0	0	Pyrolysis temperature	Elemental analysis, ash, chemical oxidation, PAH, acid hydrolysis	Fine char fraction is 2-3 time more oxidisable (24-36%) than is coarse fraction (76-58%)	n/k	n/k	*Partial*	n/s	<20, >20	Char only	n/s	Field	No	n/s	n/s	n/s	2	n/s	n/s	n/s
62	Shindo et al., 2004	Stability	Surface interactions	Static	Wood	Environmental charcoal	0	0	Soil origin	Soil density fractions; SOC	Light fractions predominantly char in volcanic ash soil; SOC is proportional to char carbon	n/k	n/k	*Partial*	n/s	n/s	Soil + charcoal	n/k	Field	Yes	Temperate	n/s	Forest, grassland, paddy	24	n/s	n/s	n/s
63	Skjemstad et al., 1999a	Quantification	Carbon-NMR spectroscopy	Static	Bagasse	Environmental charcoal	Long term (45 y)	4	Land-use change; tillage; soil depth	UV oxidation; Chemical extraction (pyrophosphate), soil density fractions	Decreasing labile SOC masked by increasing soil charcoal from cane burning	n/k	n/k	*Partial*	n/s	n/s	Soil + char	n/k	Field	Yes	n/s	n/s	Arable	8	n/s	11-33	4.8-8.1
64	Smernik and Oades, 2000	Quantification	Carbon-NMR spectroscopy	Static	various	Environmental charcoal	0	0	Soil type; hydrofluoric acid demineralisation; soil depth	Carbon NMR (single pulse, CPMAS, Bloch decay)	Aromatic (char) peak under-estimated in Cross polarisation NMR	n/k	n/k	*Partial*	n/s	n/s	Soil + char	n/k	Field	Yes	n/s	n/s	Various	8	n/s	13-77	5.1-8.0
65	Smernik et al., 2000	Quantification	Carbon NMR spectroscopy	Static	Wood	Environmental charcoal	0	0	Soil type; UV oxidation; hydrofluoric acid demineralisation; carbon NMR (single pulse / cross-polarisation)	Carbon NMR	Fast relaxing, HF, UV-oxidised NMR components accurately represent charcoal (plus carbonyl), and can be resolved by spin-counting	n/k	n/k	*Partial*	n/s	n/a	Soil + char	n/a	Field	Yes	n/a	n/a	n/s	8	n/s	13-77	5.1-7.7
66	Smernik et al., 2002	Quantification	Carbon-NMR spectroscopy	Static	Wood	Synthetic environmental charcoal	120	0	Carbon NMR parameters (spin lock, contact time)	Carbon NMR	Variable spin can account for 50% more carbon than CPMAS, spin counting improves quantification	70-350	24-72	Partial	n/s	n/s	Soil; soil + char	Very high	Lab	No	n/a	n/a	n/a	n/a	n/a	n/a	n/a
67	Spokas et al. 2009	Trace gas effects	N_2O, CH_4	Dynamic	Wood	Fast pyrolysis	100	7	Biochar addition rate, soil water content	Nitrous oxide, methane, CO_2	Biochar suppresses N_2O emission at high and very high rates, approx. 50% and reduces CH_4 oxidation, CO_2 production increased	500	n/s	Total	n/s	n/s	Soil	High, very high and extreme	Tubes	No	n/s	n/s	Arable	1	Silt loam	23	6.5
68	Steinbeiss et al., 2009	Stability	Priming	Dynamic	Pure compounds	Hydro-pyrolysis char	175	12	Treatment time; pyrolysis temperature	Microbial diversity (PLFA); Infra-red spectroscopy; ^{13}C isotope; Turnover rate, CO_2 evolution	Charcoal MRT 4-29 y	850	133	Total	n/s	n/s	Soil + char	High, extreme	Lab	No	Tropical	23	Forest, arable	2	n/s	23,40	n/s
69	Steiner et al., 2003	Microbial impacts	Microbial activity	Dynamic	Wood	Charcoal	635	2	Organic soil amendment; fertiliser nitrogen; char type	Soil basal respiration; Substrate induced respiration; Soil microbial biomass	Soil basal respiration with char and compost similar to forest, similar to litter; substrate induced respiration higher with char added	n/s	n/s	*Restricted*	n/s	n/s	Soil + char	Medium	Plots	Yes	Tropical	26	Post-forest agriculture	1	Clay	80	4.5
70	Steiner et al., 2007	Soil fertility	Crop yield	Dynamic	Wood	Charcoal	600	4	Fertiliser nitrogen; organic soil amendment; char addition rate	Crop grain yield; crop biomass yield; crop nitrogen use; soil pH; SOC, soil nutrient status	Post conversion rice yield decline is less with charcoal addition in combination with NPK, but less than with manure	n/k	n/k	*Restricted*	n/s	0-2	Soil + char	Medium	Plots	Yes	Tropical	26	Post forest agriculture	1	n/s	80	4.7
71	Steiner et al., 2008a	Soil fertility	Pyrolysis fractions	Dynamic	Wood	Charcoal	70	1	Pyrolysis fraction (char and / or condensate), soil water status	Soil basal respiration, substrate induced respiration;	Char stable but to certain limit primed by glucose; pyrolysis ash is labile and increased response	n/k	n/k	*Restricted*	n/s	n/s	Soil + char	Extreme	Lab	No	Tropical	25.8	Bare fallow	1	Clay	n/s	3.9
72	Steiner et al., 2008b	Soil fertility	Efficiency	Dynamic	Wood	Charcoal	450	2	Organic soil amendment; fertiliser nitrogen	Crop yield; ^{15}N uptake; Soil ^{15}N	Higher fertiliser nitrogen use efficiency from charcoal and/or compost addition	n/s	n/s	*Restricted*	n/s	0-2	Soil + char	Medium	Plots	Yes	Tropical	25.8	Arable	1	Fine	n/s	4.7
73	Tagoe et al., 2008	Soil fertility	Crop nitrogen uptake; charcoal MRT	Dynamic	Poultry manure	Synthetic environmental charcoal	60		Pyrolysis temperature; char addition rate	Crop nitrogen uptake; legume nodulation; crop yield; leaf chlorophyll content	Crop yield increased with same or lower uptake of phosphorus	500	n/s	Partial	9.9	n/s	Soil + char	Medium; Low	Pots	Yes	n/s	n/s	n/s	1	n/s	n/s	5.7
74	Wardle et al., 2008	Soil organic matter	Priming	Dynamic	Wood	Synthetic environmental charcoal	Long-term (10 y)	1(4)	Pyrolysis temperature; leaf litter	Residual mass, residual C + N, substrate induced respiration	Charcoal in forest humus layer promotes loss of humus	450	n/s	*Partial*	n/s	0.5-1.6	Char; soil + char	Extreme	Mesh bags	Yes	Temperate	n/s	Forest	1	n/s	n/s	n/s
75	Warren et al., 2009	Soil fertility	Phosphorus dissolution	Static	Bone	Slow pyrolysis char	145	1	Char, fertiliser phosphorus; soil pH	Phosphorus solvent extraction, CEC	Availability of phosphorus is higher from bone char than from rock phosphate, but lower than triple superphosphate	400	0.75	*Partial*	n/s	n/s	Soil + char	Medium	Lab	No	Temperate / tropical	20	Arable, agricultural grassland, forest	12	n/a	2-79	3.8-8.8

76	Yamato et al., 2006	Soil fertility	Crop yield	Dynamic	Wood bark	Charcoal	90	1	Soil type; char type; fertiliser nitrogen	Soil pH; crop + root biomass yield; crop yield; soil cation exchange capacity; mycorrhizal fungi; root biomass	Site specific positive impact on yield with and without fertilizer N for cowpea, maize and peanut crops; mycorrhizal fungi colonisation, root biomass and soil pH in maize	260-360	n/s	*Partial*	7.4	n/s	Soil + char	High	Micro-plots	Yes	n/s	n/s	Arable	1	n/s	n/s	3.9, 4.7
77	Yanai et al., 2007	Trace gas effects	N_2O	Dynamic	Green waste	Charcoal	120	6, 9	Char / ash addition rate; soil water content; pH	N_2O	No suppression of N_2O at high water content, complete at 73-78%water filled pore space, no corresponding impact for ash	n/s	n/s	n/s	9.3	0-2	Soil + char	Very high; Extreme	Lab	No	n/s	20-28	Agricultural grassland	1	Clay-loam	n/s	5.4, 6.0
78	Yedla and Dikshit, 2008	Surface reactions	Sorption	Dynamic	Wood	Charcoal; Activated charcoal	24	15	Pyrolysis temperature; time; charcoal particle size	Endosulfan, sorption; desorption	Char activity is 50% activity of activated charcoal, 90% removal with 5hr equilibrium, 10% methanol best regeneration medium	n/k	n/k	n/k	n/s	0-0.2	Char in solution	High	Lab	n/a	n/a	28	n/a	n/a	n/a	n/a	n/a
79	Yu et al., 2006	Contaminant clean-up	Agrochemical interactions	Static	Wood	Synthetic environmental charcoal	24	1	Pyrolysis temperature	Adsorption; desorption; char porosity	Adsorption hysteresis in soil is related to soil charcoal, especially char formed at high temperature	450, 850	1,.2	Partial	n/s	Powder	Soil + char	Medium; Very high	Lab	No	Sub-tropical	22	n/s	1	Sand	8	6.8

n/k = not known
n/a = not applicable
n/s = not specified

*Low <0.1% by mass or 3-4 t/ha; Medium >0.5% or 15-20 t/ha; High >2% or 60-80 t/ha; Very high > 10% or 300-400 t/ha

Italicised information is inferred

Works identified by italicised author name are not journal publications (conference proceedings, etc)

BPCA = Benzopolycarboxylic acids (black carbon marker)
CEC = Cation exchange capacity
CPMAS = Cross polarisation magic angle spinning (NMR technique to enhance sample signal)
CTO = Black carbon determination method based on chemo-thermal oxidation
DOM = Dissolved organic matter (from soil)
EDX = Energy dispersive X-ray analysis
FTICR = Fourier transform ion cyclotron resonance
GC = Gas chromatography
HyPy = Hydrogen pyrolysis
MRT = Mean residence time
NMR = Nuclear magnetic resonance spectroscopy
NPK = Nitrogen-phosphorus-potassium fertiliser
PAH = Polycyclic aromatic hydrocarbons (EPA 16 are priority PAH compounds listed by the US Environmental protection agency)
PLFA = Phospholipid fatty acids (bacterial markers)
Q10 = Measure of impact on rate with 10°C increase in temperature
SEM = Scanning electron microscopy
SOC = Soil organic carbon
SOM = Soil organic matter