Supplementary Information

Potentials, limitations, co-benefits and trade-offs of biochar applications to soils for climate change mitigation

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Table S1: Main controlling factors on the effect of biochar on agricultural yield.

Controlling factors		Observations	Ref
Biochar	Feedstock	Sludge and manure biochars have the highest positive crop yield response, followed by herbaceous and last by wood feedstock. In temperate region, all types of feedstock lead to no significant positive effect on yield. Tropical soils: Sludge and manure biochars improve yield on average by 70%. Wood and herbaceous biochars only lead to 20% increase.	(Jeffery et al. 2017; Biederman and Harpole 2013)
	CEC	Higher biochar CEC lead to higher increase in yield.	(Jeffery et al. 2017)
	Pyrolysis	There is no clear effect of pyrolysis temperature on yield response (beside for >650°C that significantly has negative effect on yield). However fast pyrolysis and hydrothermal carbonization lead to significant negative crop yield effect.	(Jeffery et al. 2017)
	Ash content	Ash content in biochar higher than 10% reduces yield increase from 30% to less than 10%.	(Jeffery et al. 2017)
	C/N ratio	Biochar's C/N ratio above 100 (biochars poor in N) lead to overall negative yield response	(Jeffery et al. 2017)
Soil	pH	Tropics: Yield response to biochar application increases as soils are more and more acidic. Temperate: Significant negative yield response (down to -30%) are observed for neutral and alkaline soils.	(Jeffery et al. 2017, Wang et al. 2019)
Management	Application rate	Tropics: Yield response seem to cross a threshold at application rate between 50-150 t biochar per ha. Temperate: Application rate should be kept between 10-50 t biochar per ha, particularly less than 50 t biochar per ha as above that threshold significantly negative yield response is significant.	(Jeffery et al. 2017)
	Fertilizer	Co-application of fertilizer with biochar can increase yield response.	(Jeffery et al. 2017)
CEC: cation exchange capacity; C/N: carbon to nitrogen ratio			

Table S2: Main controlling factors on the effect of biochar on soil and exposition to toxic compounds.

Controlling factors		Observations	Ref
Biochar	Feedstock	Biochar feedstock is the main determinant for heavy metal concentration in biochar; out of 14 heavy metals, manures-biochar had higher concentrations for 11 of them. PAHs concentrations are higher in plant-based biochar, due to higher carbon content than in manures. No clear pattern between feedstocks and VOCs production have been observed. Feedstock rich in chlorine, such as food waste, can lead to production of chlorinated compounds such as dioxins.	(Qiu et al. 2015; Dutta et al. 2017; Hale et al. 2012)
	Temperature	Production: Temperature is the main control for PAHs concentration on biochar, biochars produced at temperrature between 350 and 550°C show higher PAHs concentration than those produced at both lower or higher temperature. Dioxins production is maximum at low temperature (200-400°C). Amount of VOCs adsorbed on biochar surface decreases with increasing temperature, and is really reduced past 500°C. Once in soils: Higher temperature biochars have higher sorption capacity toward pesticide and other organic compounds, mostly due to higher porosity. Liming effect of higher temperature biochars may also be important for reducing toxicity of heavy metals.	(Hale et al. 2012; Dutta et al. 2017; Qiu et al. 2015; Ghidotti, Fabbri, and Hornung 2017; Yavari, Malakahmad, and Sapari 2015)
	Reaction time	Reaction time is an important control for the production of toxic compounds during pyrolysis. Short reaction time (e.g. fast pyrolysis) produces biochars that contain higher concentration PAHs, VOCs, and dioxins at their surface.	(Dutta et al. 2017; Hale et al. 2012)
Soil	Soil carbon	Soil carbon is an important control for the sorbing capacity of soils. Soils with high carbon content are likely to be able to sorb pollutants desorbed by biochars.	(Dutta et al. 2017)
	Pollution status	Prior level of contaminant in soils may already saturate its sorbing capacity, allowing higher desorption of biochars' contaminant.	(Dutta et al. 2017)
PAH: Polycyclic aromatic hydrocarbons; VOC: volatile organic carbon			

Table S3: CDR requirements for different temperature pathways. Taken from Huppmann et al. (2018)

Carbon sequestration (GtCO2/year)

Deploy. horizon	**2030**						**2050**						**2100**					
Temp. pathway	**Below 1.5C**	**1.5C low overshoot**	**1.5C high overshoot**	**Lower 2C**	**Above 2C**	**Higher 2C**	**Below 1.5C**	**1.5C low overshoot**	**1.5C high overshoot**	**Lower 2C**	**Above 2C**	**Higher 2C**	**Below 1.5C**	**1.5C low overshoot**	**1.5C high overshoot**	**Lower 2C**	**Above 2C**	
count	9	43	37	67	167	57	9	44	37	74	175	58	9	44	37	74	180	
mean	2.15	2.66	2.03	1.45	0.94	1.21	7.42	11.99	14.92	8.89	3.68	9.24	11.24	18.08	21.84	15.14	11.69	
std	2.40	1.85	1.55	1.29	1.22	1.51	5.40	5.29	4.75	5.68	4.12	5.85	7.67	11.02	9.88	10.91	11.78	
min	0.13	0.12	0.07	0.00	0.00	0.00	0.31	0.31	5.24	0.00	0.00	0.00	0.07	0.07	2.74	0.00	0.00	
5%	0.13	0.38	0.08	0.00	0.00	0.00	1.08	1.69	8.27	0.00	0.00	0.00	0.46	1.77	9.53	0.00	0.00	
10%	0.13	0.39	0.49	0.00	0.00	0.02	1.86	5.12	9.34	0.00	0.00	1.66	0.85	6.08	13.45	0.00	0.00	
15%	0.19	0.42	0.58	0.00	0.00	0.09	2.74	6.40	9.77	0.56	0.00	3.85	1.99	8.87	14.52	0.43	0.00	
25%	0.40	0.80	0.80	0.36	0.00	0.20	4.74	7.61	12.40	6.06	0.01	5.50	5.76	11.95	15.96	8.13	0.23	
35%	0.41	1.49	1.12	0.49	0.07	0.46	5.41	10.34	12.83	7.30	1.04	7.05	10.75	14.77	16.29	11.26	3.46	
50%	0.42	2.66	1.65	1.09	0.36	0.91	6.25	13.55	15.09	9.58	2.48	9.49	12.96	17.05	22.04	14.91	8.17	
75%	3.26	4.14	2.93	2.49	1.46	1.54	9.13	16.02	17.46	12.08	5.71	11.45	14.88	21.68	25.52	21.31	18.40	
95%	5.83	5.39	4.38	3.75	3.49	3.21	15.99	18.07	22.41	18.64	11.91	20.13	21.22	30.17	43.57	31.10	35.94	
max	5.93	6.30	7.63	4.56	5.77	9.78	17.34	20.21	28.32	24.63	22.90	29.96	23.13	62.87	45.43	45.65	48.73	

Table S4: Total cumulative CDR requirements for different temperature pathways. Taken from Huppmann et al. (2018)

Carbon sequestration (GtCO2)

Temperature pathway	**Below 1.5C**	**1.5C low overshoot**	**1.5C high overshoot**	**Lower 2C**	**Above 2C**	**Higher 2C**
count	7	43	35	63	158	51
mean	611.80	828.28	1,042.61	855.82	484.52	983.39
std	196.00	363.49	312.34	351.99	477.39	390.22
min	268.06	0.00	480.78	112.88	0.00	247.13
5%	335.11	126.90	632.32	410.27	0.00	503.11
15%	469.21	427.87	809.53	517.67	0.00	669.45
25%	525.16	558.79	863.92	657.12	3.70	744.97
50%	619.62	903.80	919.60	827.42	413.91	890.97
75%	753.22	1,033.10	1,207.02	1,002.16	819.15	1,174.84
95%	825.71	1,399.39	1,592.01	1,482.78	1,323.81	1,768.92
max	838.19	1,493.92	1,858.40	1,978.85	2,034.77	2190.55

Table S5: Key biochar properties and their controlling factors under slow pyrolysis.

Property	Controlling factor	Observations	Ref
Yield and carbon content	Feedstock	For similar pyrolysis temperature, ligno-cellulosic materials (e.g. woody and herbaceous feedstocks) have higher yield and carbon content, than manures or sludge.	(Li et al. 2019)
	Temperature	Yield decreases with increasing temperature and reaches a plateau at about 600°C for wood/herbaceous feedstock, and 400°C for manures/biosolids. Carbon content in biochar increases linearly with pyrolysis temperatures.	(Li et al. 2019)
	Additives	Potassium (K) increases the amount of carbon retention in biochar by 45%.	(Mašek et al. 2019)
Porosity and surface area	Feedstock	Macroporosity retains the cell structure of feedstock. Woody feedstock have much higher surface area than other feedstocks: Woody > herbaceous > manures > sludge (surface area is divided by a factor two between each categories).	(Li et al. 2019; Wildman and Derbyshire 1991; Gray et al. 2014)
	Temperature	Higher pyrolysis temperature increases biochar's microporosity. Surface area increases with pyrolysis temperature.	(Li et al. 2019)
Ash	Feedstock	Ash content increases, as sludge/digestate > manures > herbaceous > wood. Ash content also changes with feedstock. Herbaceous-derived biochars have higher N and P content than wood-derived biochar, but usually less base cation (Ca^{2+}, Mg^{2+}, K^{+}) (especially compared to softwood). Hardwood-biochar have the most Sulfur. Manures-biochar are both the richest in N and P and base cations.	(Li et al. 2019; Ippolito et al. 2015)
	Temperature	Ash content increases with pyrolysis temperatures.	(Li et al. 2019)
H/C_{org}	Feedstock	Wood and herbaceous feedstock have similar H/C_{org} ratios at a given temperature. Manures and sludge have much higher ratios. Indicate a higher level of aromatic condensation in biochar produced from lignocellulosic biomass.	(Li et al. 2019; Xiao, Chen, and Chen 2016)
	Temperature	H/C_{org} decreases with increasing pyrolysis temperature. Indicate a higher level of aromatic condensation of biochar at higher temperature.	(Li et al. 2019; Weber and Quicker 2018)
O/C_{org}	Feedstock	Wood and herbaceous feedstock have similar O/C_{org} ratios at a given temperature. Manures have much higher ratios.	(Li et al. 2019)
	Temperature	O/C_{org} decreases with increasing pyrolysis temperature	(Li et al. 2019)
C/N	Feedstock	Wood has much higher C/N ratio (much poorer in N compared to C), about twice as high as for herbaceous feedstock. Manures and sludge are much richer in N compared to C, by a factor 10 compared to wood.	(Li et al. 2019)
	Temperature	C/N increases with increasing pyrolysis temperature, biochar becomes poorer in N compared to C.	(Li et al. 2019)
CEC (negative charges on	Feedstock	Wood and manures derived biochars have lower CEC than herbaceous and sludge.	(Li et al. 2019)

biochar)	Temperature	CEC decreases with pyrolysis temperature. Due to lower O/C_{org} and lower H/C_{org}.	(Li et al. 2019)
	pH conditions	Different oxygen functional groups have diffeent pKa, and are deprotonated under different pH conditions. CEC increases with increasing pH, as at higher pH, acids and alcohol of higher pKa are successively deprotonated.	(Banik et al. 2018; Chen et al. 2015; Szymański et al. 2002)
	Aging	During aging in soils, biochar surface is oxidized, increasing O/C_{org} ratios and its CEC.	(Mia, Dijkstra, and Singh 2017)
AEC (positive charges on biochar)	Feedstock	Wood biochar have higher AEC than herbaceouss feedstock.	(Lawrinenko and Laird 2015; Banik et al. 2018)
	Temperature	Pyrolysis temperature increases AEC.	(Lawrinenko and Laird 2015; Banik et al. 2018)
	pH conditions	AEC can be significant in acidic pH but not at neutral or alkaline pH, and quickly decreases with increasing pH. AEC comes mostly from pH dependant sites that are protonated in acidic conditions.	(Lawrinenko and Laird 2015)
	Aging	Very little AEC is structurally stable, and will disappear quickly under soil aging.	(Lawrinenko et al. 2016)
	Additives	Pre-treatment of feedstock with aluminum and iron can increase AEC at higher pH (alkaline conditions).	(Lawrinenko et al. 2017; Banik et al. 2018)
Surface charge	Temperature	The pH at which global charge of surface biochar is null increases with increasing pyrolysis temperature.	(Banik et al. 2018)
pH and alkalinity	Feedstock	Wood biochar are more acidic (range of pH 4-8) than herbaceous (range of pH 6-12). Manures are the most alkaline (range of pH 8-10). Wood biochar have little alkalinity, while herbaceous and manures have higher level of alkalinity. Carbonates in ashes are a major source of alkalinity. Structural low-pKa acid groups ($5 < pKa < 6.4$) can be an important source of alkalinity at low temperature for herbaceous feedstock Wood-derived biochars have higher base cation concentration than herbaceous-derived biochars; but much lower than manures.	(Li et al. 2019; Fidel et al. 2017; Ippolito et al. 2015)
	Temperature	Temperature increases biochars pH and alkalinity. Structural alkalinity decreases with increasing temperature, while temperature increases the amount of carbonates produced during pyrolysis.	(Li et al. 2019; Fidel et al. 2017)
Conductivity	Feedstock	Higher mineral content in herbaceous biochar was linked to a higher electron exchange capacity	(Klüpfel et al. 2014)
	Temperature	Wood charcoal was shown to act as an insulator, a semiconductor and a conductor, respectively at <300 °C, 300 °C–800 °C and >800 °C.	(Joseph et al. 2015; Klüpfel et al. 2014)

		Redox activity is controlled by electronic donating phenolic moeities for low temperature biochars, electron accepting quinone moieties for mid-temperature, and quinone and possibly aromatics for high-temperature biochars.	
C_{org}: organic carbon (exclude carbon present in biochar's ash as carbonates); CEC: cation exchange capacity; AEC: anion exchange capacity			

Table S6: Main controlling factors of the effect of biochar on SOC priming.

Controlling factors		Observations	Ref
Biochar	Feedstock	Crop and wood derived biochar significantly induce negative priming. Sludges and manures derived biochars lead to positive priming mostly. Grass biochars lead to both positive and negative priming with null net effect overall.	(Ding et al. 2018)
	Temperature	Pyrolysis temperatures above 500°C lead to significant negative priming. Negative priming is much stronger for pyrolysis temperature above 600°C.	(Ding et al. 2018)
	Nitrogen	Increasing C/N ratio of biochar increases negative priming. Biochar with more than 4% nitrogen switch from negative to positive priming, however variations in response are important and not statistically significant.	(Ding et al. 2018)
	Carbon	Pyrolysis time, temperature and feedstock control the amount of carbon in biochars. A carbon content over 50% in biochar lead to significant negative priming.	(Ding et al. 2018)
	Aging	Charcoal deposits in historical stabilizes recent input of carbon better than adjacent soils without charred materials.	(Kerré et al. 2016; Hernandez-Soriano et al. 2016; Kerré, Willaert, and Smolders 2017)
Soil	SOC	Soils with less than 1% SOC lead to significant positive priming.	(Ding et al. 2018)
	C/N ratio	Negative priming is larger at soil C/N below 11-12. Above that value, negative priming is not statistically significant.	(Ding et al. 2018)
	Texture	Soil texture seems to have little effect on priming of SOC, being overall negative. Negative priming is more important at clay content above 50%.	(Ding et al. 2018; J. Wang, Xiong, and Kuzyakov 2016)
	pH	Negative priming is more important at soil pH above 6 and slightly decreases with increasing soil pH.	(Ding et al. 2018)
SOC: soil organic carbon; C/N: carbon to nitrogen ratio			

Table S7: Main controlling factors of the effect of biochar on soil methane (CH_4) emissions or uptake.

Controlling factors		Observations	Ref
Biochar	Feedstock	Different meta-analysis draw different conclusion regarding the effect of biochar's feedstock on soil methane emissions.	(He et al. 2017; Ji et al. 2018; Jeffery et al. 2016)
	Temperature	Increasing pyrolysis temperature decreases methane release from 'methane source' soils, but also the oxidative potential of 'methane sink' soils.	(Ji et al. 2018)
	pH	Upland soils see reduced methane uptake for biochars with pH below 7 to a positive increase in uptake for biochars with pH >9.	(Ji et al. 2018; He et al. 2017)
Soil	Moisture	Flooded soils (paddy rice) see their methane emissions reduced after biochar amendment. Upland soils that are 'methane source' see their emissions reduced. Upland soils that are 'methane sink' see their sink capacity reduced.	(Ji et al. 2018; Jeffery et al. 2016)
	pH	In upland soils, biochar reduced methane uptake in acidic and neutral soils. In flooded soils, biochar increases methane release in acid soils, but decreases it in neutral and alkaline soils.	(Ji et al. 2018; Jeffery et al. 2016)
	Texture	Biochar has more pronounced effect on medium textured soils: reducing soil methane emissions from 'methane source' soils and reducing methane sink capacity from 'methane sink' soils. Fine soils see their methane emissions increase after biochar treatment.	(Ji et al. 2018)
Management	Fertilization	Unfertilized soils show higher response to biochar addition regarding decreasing release and uptake of methane. Upon application of organic-N fertilizer, biochar increases the sink capacity 'methane sinks' Both application of organic or synthetic N, decrease emissions of 'methane source' after application of biochar. N-fertilization rate may also influence soil response to biochar application: below 120kgN/ha increasing methane sink/decreasing methane emissions, while more than 120 kgN/ha has opposite effect.	(Jeffery et al. 2016; Ji et al. 2018)
	Application rate	Biochar application rate below 20 t/ha may be beneficial for enhancing soil methane sinks, but increase methane emissions from 'methane source' soils. After that threshold, increasing biochar application rate decreases both methane emissions from source, and decreases sink potential of sinks.	(Ji et al. 2018)

Table S8: Main controlling factors on the effect of biochar on soil nitrogen availability.

Controlling factors		Observations	Ref
Biochar	Feedstock	Crop residues are feedstocks that most significantly reduce availability of nitrogen in agroecosystems.	(Gao, DeLuca, and Cleveland 2019)
	Temperature	Immobilization of both NO_3^- and NH_4^+ is minimal at medium pyrolysis temperature (400-600°C)	(Gao, DeLuca, and Cleveland 2019; T. T. N. Nguyen et al. 2017)
	AEC and CEC	NO_3^- preferentially sorb on AEC sites, while NH_4^+ on CEC sites.	(Ippolito et al. 2015)
	Aging	Via decrease in AEC and increase in CEC.	(Ippolito et al. 2015)
Soil	pH	Soil pH is noted as being an important controlling factor of biochar's effect on soil nitrogen availibility by both Gao and colleagues and Nguyen and colleagues, but they disagree.	(Gao, DeLuca, and Cleveland 2019; T. T. N. Nguyen et al. 2017)
Management	Fertilizer	Biochar reduces NH_4^+ availability under all N-fertilizer type, but organic-N application. Co-application of fertilizer and biochar may reduces risk of immobilizing nitrate after biochar application. Urea and NH_3-based fertilizers have potential to mitigate nitrate deficiency.	(Gao, DeLuca, and Cleveland 2019; T. T. N. Nguyen et al. 2017)
	Application rate	Increasing application rate of biochar tend to reduce nitrogen availability.	(Gao, DeLuca, and Cleveland 2019; T. T. N. Nguyen et al. 2017; Borchard et al. 2019)

Table S9: Main controlling factors of the effect of biochar on soil ammonia (NH_3) volatilization rate.

Controlling factors		Observations	Ref
Biochar	pH	Biochars with pH above 9 statistically increase NH_3 volatilization. Biochar pH below 7 tend to increase NH_3 volatilization as well. In between it may or may not decrease NH_3 volatilization.	(Liu et al. 2018)
	Feedstock	Manure biochars increase NH_3 volatilization, because of their high alkalinity. Biochar from woody biomass reduces NH_3 volatilization more efficiently because of higher sorption capacity.	(Liu et al. 2018; Sha et al. 2019)
	Aging	Aging of biochar in soils increases its CEC and Biochar liming effect is only temporary. Enhancement of ammonia volatilization after biochar application is expected to be only temporary, in the long term biochar may reduce soil NH_3 volatilization.	in text begining p.219 (Liu et al. 2018)
Soil	pH	Biochar particularly increases NH_3 volatilization in acidic soils with pH below 5-6 and has little effect, even potentially reducing emissions over the rest of the pH range.	(Liu et al. 2018; Sha et al. 2019)
	Native SOC	Biochar applied to soils with low native organic carbon (<2%) increase NH_3 volatilization Above 3% SOC, biochar reduction in NH_3 volatilization is statistically significant.	(Liu et al. 2018; Sha et al. 2019)
	Texture	The 2 meta-analysis available contradict each other regarding the effect of biochar in fine soil: Sha et al. (2019) find a significant decrease in NH_3 volatilization in finer soils, while Liu et al. (2018) a significant increase. Liu et al.'s explanation of reduced resistance to volatilization due to higher aeration in fine soil after biochar application is a compelling argument in their case.	(Liu et al. 2018; Sha et al. 2019)
	CEC	Soils with low CEC see enhancement volatilization upon biochar application. This enhancement decreases with increase soil CEC.	(Liu et al. 2019)
Management	Application rate	Higher application rate tend to increase NH_3 volatilization compared to controls, usually explained by a higher liming effect.	(Liu et al. 2018; Sha et al. 2019)
	Fertilizer	Biochar application may be able to handle low N-fertilization (<200kg/ha) as an overall decrease in ammonia volatilization is observed, but higher fertilizer application rate will see higher NH_3 volatilization. Using organic fertilizer or urea do not enhance NH_3 volatilization, but ammonium fertilizer does.	(Sha et al. 2019)

Table S10: Main controlling factors on the effect of biochar on soil phosphorus availability.

Controlling factors		Observations	Ref
Biochar	Feedstock	Biochar derived from crop residues and manures increase the most phosphorus availability.	(Gao, DeLuca, and Cleveland 2019)
	Temperature	Biochar produced at lower pyrolysis temperatures allows for more available phosphorus. At high temperature stable compounds of phosphorus are produced from the feedstock, limiting its supply to plants. Temperature above 600°C may reduce soil P-availability.	(Gao, DeLuca, and Cleveland 2019; Glaser and Lehr 2019)
	Ash	Ca^{2+} and Mg^{2+} present in the biochar ashes can lower availability of phosphorus by precipitation.	(Ippolito et al. 2015)
Soil	Texture	Medium textured soils have higher responses to biochar application, with an increase in phosphorus availability.	(Gao, DeLuca, and Cleveland 2019)
	pH	Soil with pH over 7.5 may experience lower P availability after biochar application, potentially due to liming effect reducing P-availability, or Ca-P precipitation.	(Gao, DeLuca, and Cleveland 2019; Glaser and Lehr 2019)
Management	Application rate	Increasing application rate was found to increase phosphorus availability, mostly as more biochar brings more phosphorus to the soil. Increased availability is significant at application rate above 10 tonnes biochar per hectare. However, at higher application rate, liming (soil pH increase) may be more important.	(Gao, DeLuca, and Cleveland 2019; Glaser and Lehr 2019)

Table S11: Main controlling factors on the effect of biochar on soil nutrient leaching.

Controlling factors		Observations	Ref
Biochar	Ash	Nutrient brought with biochar can readily be leached out of soils.	(Ippolito et al. 2015)
Soil	Hydraulic conductivity	Increase in soil hydraulic conductivity after biochar application can lead to an increase in the amount of leached nutrients, if they are made more available after biochar application. As such, biochar may reduce nutrient leaching in coarser soil, and may increase it in finer soils.	(Laird and Rogovska 2015)
Management	Application rate	In case of leaching of biochar's nutrient, higher application rate will lead to more leaching. Application rate will also modulate leaching rate as they affect nutrient availability and soil water retention and conductivity.	(Ippolito et al. 2015; Laird and Rogovska 2015)

Table 12: Main controlling factors on the effect of biochar on soil water availability and soil hydraulic conductivity.

Controlling factors		Observations	Ref
Biochar	Hydro-phobicity	Biochar hydrophobicity is an important control on its water uptake potential.	(Gray et al. 2014; Kinney et al. 2012)
	Porosity	Biochar's macroporosity is more important for water retention than its microporosity. Choice of feedstock with appropriate macrostructure is important.	(Gray et al. 2014; Kinney et al. 2012)
	Particle size and shape	Depending on biochar particle size, biochar can clog or increase the size of soil pores. Clogging happen when biochar particle size is lower than the size of soil interpores. As a consequence, both soil hydraulic conductivity and soil water availability increases. Shape of biochar particles has been suggested to influence soil's interpores structure by disrupting and modifying the interpores size distribution. But very fine biochar particles can loose their porosity, in particular macroporosity.	(Sun and Lu 2014; Trifunovic et al. 2018)
Soil	Water repellency	Biochar's effect on soil water repellency has been little studied. Most of the studies reported no effect of biochar, a few reported conflicting results.	(Blanco-Canqui 2017; Hallin et al. 2015)
	Texture	Coarse soil see higher increase in soil water availability than finer soil, due to increase in mesopore that allow retention of water after biochar application. Biochar reduces water infiltration and hydraulic conductivity in coarse soil, and the opposite for fine soils. Thus improving soil hydrology in both cases, though the effect is usually more important in coarse soils. Medium textured soils receive less benefit from biochar application.	(Omondi et al. 2016; Blanco-Canqui 2017)
	Soil pore size	Soil pore size distribution is important for soil hydrology. Biochar may influence soil pore size distribution via its particles size and shape, and its effect on soil aggregates. Biochar has effect on aggregate stability, which may prevent clogging, and aggregate size, and may increase soil pore size.	(Sun and Lu 2014; Trifunovic et al. 2018; Blanco-Canqui 2017)
	Run-off volume	Biochar reduced run-off volume in 4 out of 6 studies, from 5 to 50% reduction.	(Blanco-Canqui 2018)
Manage-ment	Application rate	Soil available water capacity increases with increasing biochar application rate. But a minimum application rate may be required to observe significant response. Most studies that observed increase in soil available water used application rate >25 t biochar/ha. Soil saturated hydraulic conductivity increases with biochar application rate, but a minimum amount of biochar may be required before significant response (~>20 t biochar/ha).	(Omondi et al. 2016; Blanco-Canqui 2017)

Table S13: Classification of the LCA studies under type of feedstock and origin (residues, dedicated plantations or waste) and for which life-cycle stages the results were used in figure 3 in the main text.

References	**Herbaceous**	**Wood**	**Organic waste**		**Residue**	**Dedicated plantation**	**Waste**		**Supply-chain**	**Avoided emissions**	**Carbon sequestration**	**Effects on soils**	**Total**
(Roberts et al. 2010)	**x**	**x**			**x**	**x**	**x**		**x**	**x**	**x**	**x**	**x**
(Hammond et al. 2011)	**x**	**x**			**x**	**x**			**x**	**x**	**x**	**x**	**x**
(Ibarrola, Shackley, and Hammond 2012)	**x**	**x**	**x**		**x**		**x**		**x**	**x**	**x**	**x**	**x**
(Meyer et al. 2012)	**x**	**x**			**x**				**x**	**x**	**x**	**x**	**x**
(Field et al. 2013)		**x**			**x**				**x**	**x**	**x**	**x**	**x**
(Lugato et al. 2013)		**x**			**x**								
(T. L. T. Nguyen, Hermansen, and Nielsen 2013)	**x**				**x**								
(Cao and Pawlowski 2013)			**x**				**x**						**x**
(Sparrevik et al. 2013)	**x**				**x**								
(Z. Wang et al. 2014)	**x**				**x**				**x**	**x**	**x**	**x**	**x**
(Sparrevik et al. 2014)		**x**			**x**								
(Peters, Iribarren, and Dufour 2015)		**x**				**x**							**x**
(Homagain et al. 2015)		**x**			**x**								**x**
(Thornley et al. 2015)		**x**				**x**							**x**
(Miller-Robbie et al. 2015)			**x**				**x**						**x**

(Clare et al. 2015)	**x**				**x**								**x**
(Mohammadi et al. 2016)	**x**				**x**								
(Pietro Bartocci et al. 2016)		**x**				**x**							**x**
(Muñoz et al. 2017)	**x**	**x**			**x**								**x**
(Ericsson et al. 2017)		**x**				**x**							
(Smebye et al. 2017)		**x**			**x**								
(Llorach-Massana et al. 2017)	**x**				**x**								**x**
(Robb and Dargusch 2018)	**x**				**x**								**x**
(Mohammadi et al. 2019a)			**x**				**x**						**x**
(Mohammadi et al. 2019b)			**x**				**x**						**x**
(Rajabi Hamedani et al. 2019)		**x**	**x**			**x**	**x**						**x**
(Barry et al. 2019)			**x**				**x**						
(Azzi, Karltun, and Sundberg 2019)		**x**			**x**				**x**	**x**	**x**	**x**	**x**
(Lu and El Hanandeh 2019)		**x**			**x**								**x**
(Tadele et al. 2019)	**x**					**x**			**x**				
(Thers et al. 2019)	**x**					**x**							
(Uusitalo and Leino 2019)	**x**	**x**			**x**								
(Xu et al. 2019)	**x**				**x**								

Table S14: Classification of LCA studies according to the type of impact/indicator they include in the analysis: global warming potential (GWP), acidification potential (AP), ozone depletion potential (ODP), eutrophication (EP), smog formation, respiratory effects (REP), carcinogenic potential (CP), non-carcinogenic potential (NCP), ecotoxicity (ECT), and fossil fuel depletion (FFD), end-points (e.g. Human health, Ecosystem health, Resource depletion), Energy use (e.g. life-cycle energy use, cumulative energy use), cost (e.g. life-cycle cost, environmental valuation)

References	**GWP**	**AP**	**ODP**	**EP**	**REP**	**CP**	**NCP**	**ECT**	**FFD**		**End Points**	**Energy use**	**Cost**
(Roberts et al. 2010)	**x**											**x**	**x**
(Hammond et al. 2011)	**x**												
(Ibarrola, Shackley, and Hammond 2012)	**x**												
(Meyer et al. 2012)	**x**												
(Field et al. 2013)	**x**												**x**
(Lugato et al. 2013)	**x**												
(T. L. T. Nguyen, Hermansen, and Nielsen 2013)	**x**	**x**		**x**	**x**				**x**				
(Cao and Pawlowski 2013)	**x**											**x**	
(Sparrevik et al. 2013)	**x**				**x**				**x**				
(Z. Wang et al. 2014)	**x**												
(Sparrevik et al. 2014)	**x**				**x**								
(Peters, Iribarren, and Dufour 2015)	**x**	**x**		**x**								**x**	
(Homagain et al. 2015)		**x**			**x**								
(Thornley et al. 2015)	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**		**x**		
(Miller-Robbie et al. 2015)			**x**				**x**					**x**	
(Clare et al. 2015)	**x**				**x**								**x**
(Mohammadi et al. 2016)	**x**												
(Pietro Bartocci et al. 2016)	**x**												
(Muñoz et al. 2017)	**x**			**x**	**x**	**x**	**x**		**x**				
(Ericsson et al. 2017)	**x**											**x**	

(Smebye et al. 2017)											**x**		
(Llorach-Massana et al. 2017)	**x**												
(Robb and Dargusch 2018)	**x**												
(Mohammadi et al. 2019a)	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**				
(Mohammadi et al. 2019b)	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**				
(Rajabi Hamedani et al. 2019)	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**		**x**	**x**	**x**
(Barry et al. 2019)	**x**							**x**					
(Azzi, Karltun, and Sundberg 2019)	**x**												
(Lu and El Hanandeh 2019)	**x**											**x**	**x**
(Tadele et al. 2019)	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**				
(Thers et al. 2019)	**x**												
(Uusitalo and Leino 2019)	**x**												
(Xu et al. 2019)	**x**												

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