Supplementary Information

Title: Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls

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Running Title: Biochar effect on crop yield: a meta-analysis

Figure S1 Map of experimental sites from the peer-reviewed literature used in the current meta-analysis. This map was generated with Google My Maps (accessed January 2019).

Figure S2 Proportional changes in crop yield of the "fertilized control" for each level of the individual categories over the "non-fertilized control". The red dotted lines represent the overall mean change in crop yield among all studies combined. The numbers in parentheses show the number of pairwise comparisons on which the statistic is based. The data used to generate this figure is provided in Supplementary Information (Table S7).

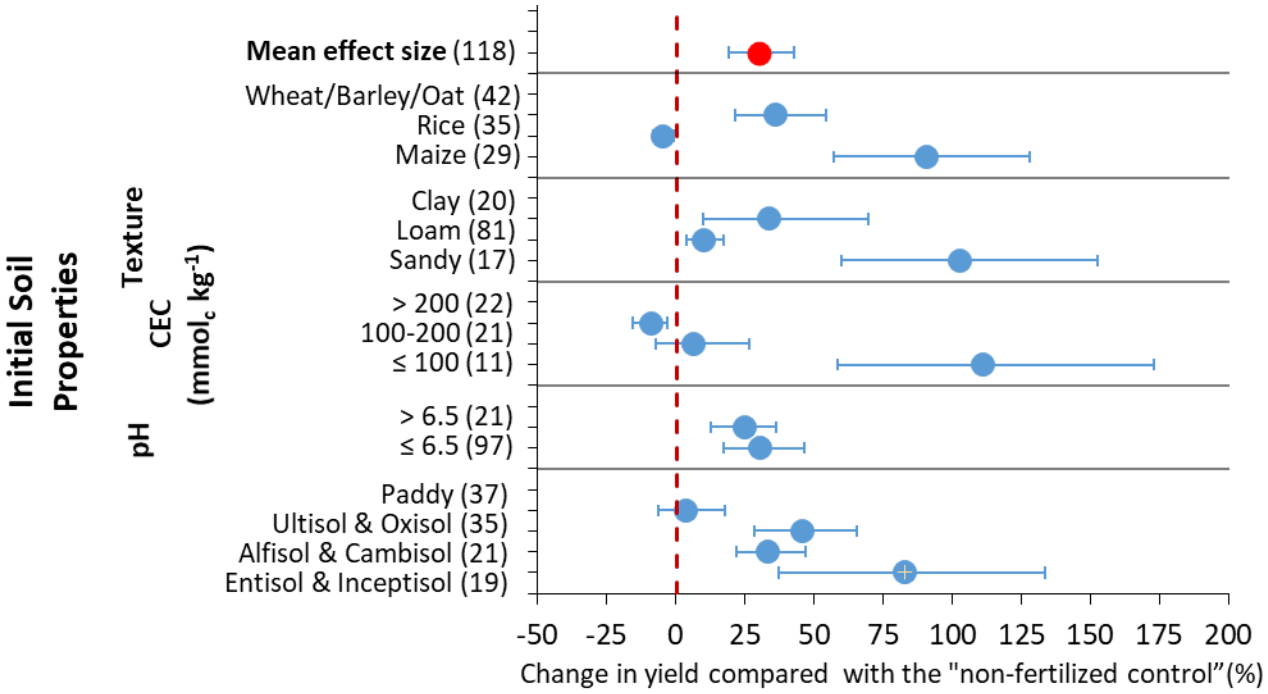

Figure S2 Proportional changes in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) for each level of the individual categories over the "non-fertilized control" when excluding rice crops. The red dotted lines represent the overall mean change in crop yield among all studies combined. The numbers in parentheses show the number of pairwise comparisons on which the statistic is based. The data used to generate this figure is provided in Supplementary Information (Table S8).

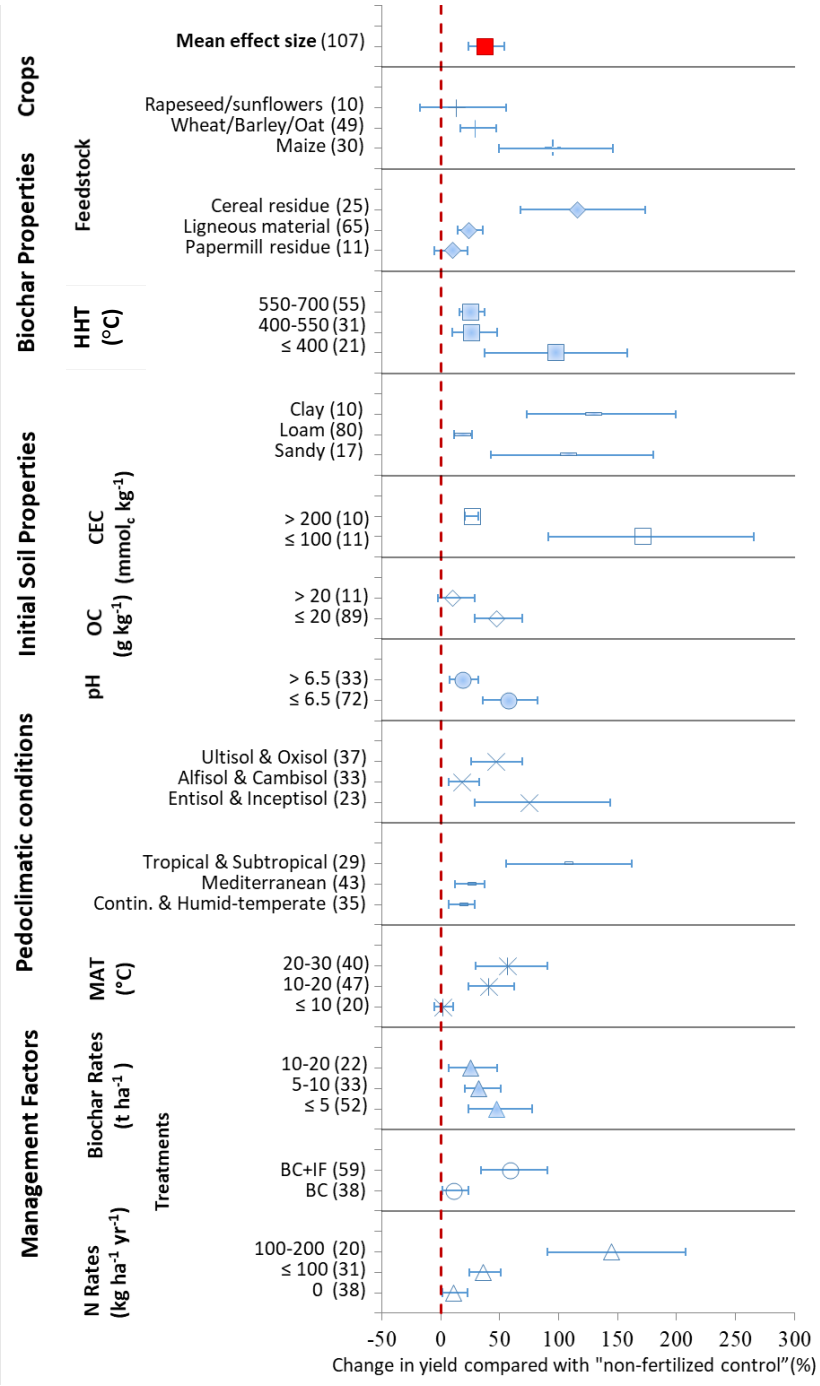

Figure S3 Proportional changes in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) for each level of the individual categories over the "fertilized control" when excluding rice crops. The red dotted lines represent the overall mean change in crop yield among all studies combined. The numbers in parentheses show the number of pairwise comparisons on which the statistic is based. The data used to generate this figure is provided in Supplementary Information (Table S9).

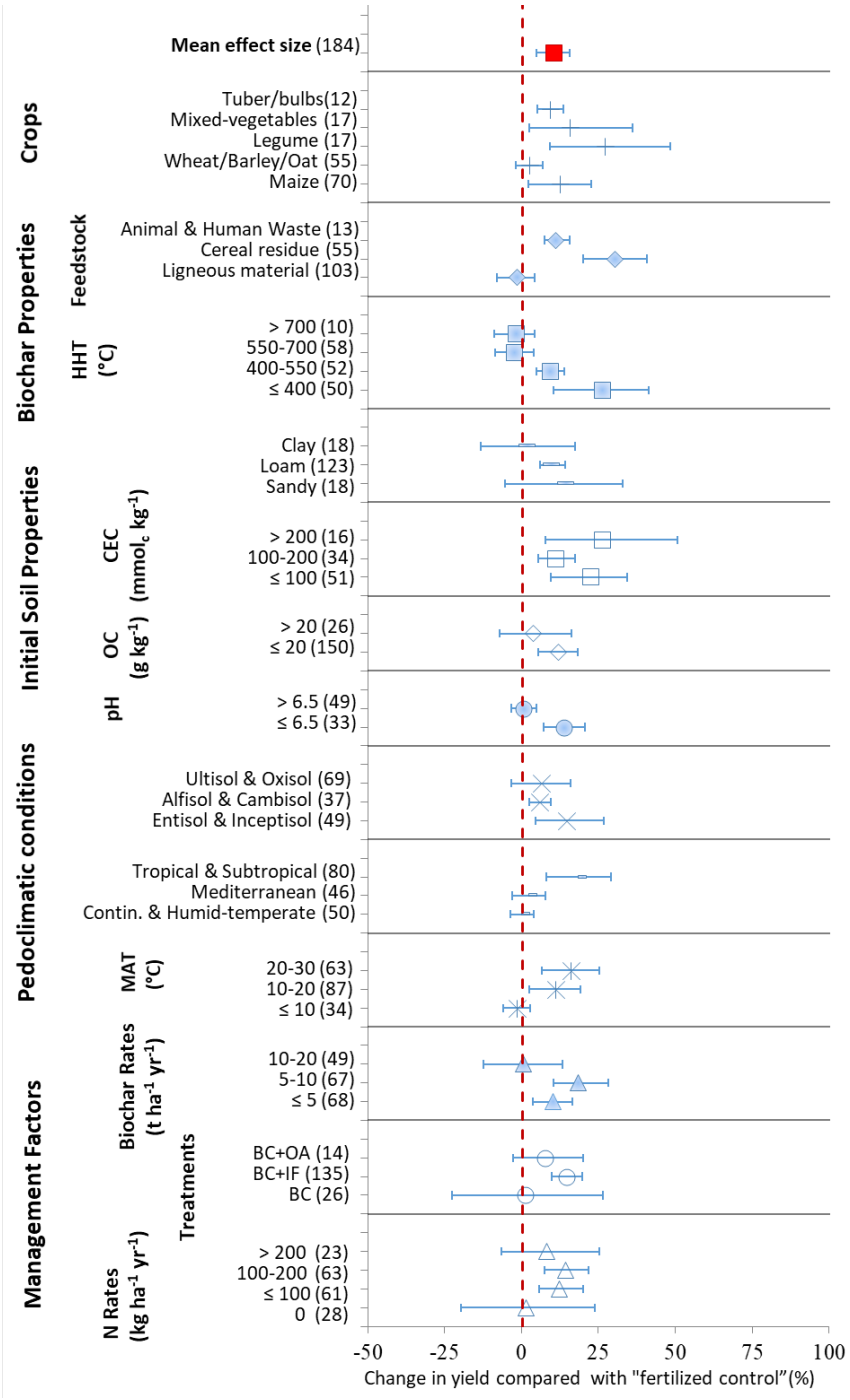

Table S1 Methodology used for measuring CEC when provided by the authors.

Abiven *et al.* (2015)	1 M NH_4NO_3
Agegnehu *et al.* (2015)	Not specified
Asai *et al.* (2009)	Not specified
Baronti *et al.* (2010)	NH_4OAc
Bian *et al.* (2014)	NH_4OAc at pH 7
Blackwell *et al.* (2010)	Not provided
Cui *et al.* (2017)	Not provided
Gautam *et al.* (2017)	NH_4OAc
Griffin *et al.* (2017)	NH_4^+ replacement
Haider *et al.* (2017)	Not provided
Li *et al.* (2017)	Not specified
Liu *et al.* (2014a)	Not specified
Major *et al.* (2010)	NH_4OAc
Nelissen *et al.* (2015)	Not provided
Tammeorg *et al.* (2014)	Not provided
Solaiman *et al.* (2010)	NH_4Cl
Steiner *et al.* (2008)	NH_4OAc
Suddick & Six (2013)	BaOAc saturation and cation replacement
Tammeorg *et al.* (2014)	Not provided
Vaccari *et al.* (2015)	$BaCl_2$ at pH 8.2
Zhang *et al.* (2010)	Not provided
Zhang *et al.* (2012a)	Not provided
Zhang *et al.* (2012b)	Not provided
Van Zwieten *et al.* (2015)	$BaCl_2/NH_4Cl$
Güereña *et al.* (2013)	NH_4OAc at pH 7
Cornelissen *et al.* (2013)	NH_4OAc at pH 7
Hammond *et al.* (2013)	Not specified
Zhang *et al.* (2016)	Not provided
Slavich *et al.* (2013)	NH_4Cl at pH 7
Gaskin *et al.* (2010)	Not provided
Liu *et al.* (2014b)	Not provided
Liu *et al.* (2016)	Not provided
Liu *et al.* (2012)	Not provided
Kimetu *et al.* (2008)	NH_4OAc at pH 7
Mekuria *et al.* (2014)	Not specified
Agegnehu *et al.* (2016a)	NH_4OAc
Islami *et al.* (2011)	NH_4OAc
Martinsen *et al.* (2014)	NH_4OAc at pH 7
Zhang *et al.* (2013)	NH_4OAc at pH 7
Agegnehu *et al.* (2016b)	NH_4OAc
Masto *et al.* (2013)	Not specified
Li *et al.* (2015)	NH_4OAc
Paneque *et al.* (2016)	Not provided
Xiang *et al.* (2015)	Not provided
Sukartono *et al.* (2011)	NH_4OAc at pH 7
Faloye *et al.* (2017)	NH_4OAc
Backer *et al.* (2016)	Not provided
Koga *et al.* (2017)	Not provided
Yeboah *et al.* (2017)	Not provided
Vitkova *et al.* (2017)	Not provided
Si *et al.* (2018)	NH_4OAc
Mierzwa-Hersztek *et al.* (2016)	Not provided
Mierzwa-Hersztek *et al.* (2017)	Not provided
Watanabe *et al.* (2014)	Not provided
Horák *et al.* (2017)	Not provided
Arif *et al.* (2017)	Not provided

Table S2. Proportional changes (mean, and lower and upper confidential intervals) in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) for each level of the individual categories over the "non-fertilized control".

Category	Groups	n	Change (%)	Lower CI	Upper CI
N application rate	0 kg/ha/yr	59	7.0	-0.4	16.2
	≤100 kg/ha/yr	45	27.1	17.7	38.6
	100-200 kg/ha/yr	20	145.2	91.0	209.1
	>200 kg/ha/yr	10	60.3	18.3	129.8
Treatment	BC	62	6.9	-0.8	15.7
	BC+IF	78	47.5	29.6	70.3
Biochar application rate	≤ 5	60	40.2	18.2	67.1
	5-10	54	24.4	15.8	35.5
	>10	36	17.2	4.5	32.8
Annual mean temperature	≤10	20	2.0	-5.0	0.3
	10-20	55	36.0	22.6	52.6
	20-30	75	34.5	18.4	54.9
Climate	Continental and humid-temperate	35	16.3	-7.8	46.7
	Mediterranean	43	23.3	12.2	37.0
	Tropical and subtropical	72	40.6	20.7	67.4
Soil classification	Entisol & Inceptisol	23	75.1	29.1	143.0
	Alfisol & Cambisol	33	18.2	7.9	32.9
	Ultisol & Oxisol	37	46.6	26.2	71.3
	Paddy	45	10.8	0.6	22.1
soil pH	≤6.5	107	36.9	22.7	53.1
	>6.5	41	18.3	8.4	30.3
SOC	≤20 g/kg	128	34.3	21.8	50.3
	>20 g/kg	15	7.4	-2.7	21.1
soil CEC	< 100 $mmol_c/kg$	12	160.9	85.1	245.1
	100-200 $mmol_c/kg$	28	19.7	7.3	37.3
	>200 $mmol_c/kg$	24	10.5	-0.2	22.9
Soil texture	Sandy	17	108.4	42.8	183.7
	Loam	110	15.4	10.2	21.8
	Clay	23	39.8	13.8	76.9
Pyrolysis temperature	≤400	21	97.4	39.1	161.6
	400-550	39	23.8	10.8	41.4

	550-700	90	17.3	9.5	25.5
Feedstock	Papermill residue	11	10.1	-3.6	23.3
	Ligneous material	100	17.0	10.3	24.7
	Cereal residue	33	90.4	48.9	135.5
Crop	Maize	30	95.5	48.7	151.8
	Rice	43	4.0	-2.2	11.2
	Wheat/barley/oat	49	29.2	16.8	46.6
	Rapeseed/sunflowers	10	13.1	-4.0	34.1
Grand mean		150	28.7	19.0	40.5

Table S3. Proportional changes (mean, and lower and upper confidential intervals) in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) for each level of the individual categories over the "fertilized control".

Category	Groups	n	Change (%)	Lower CI	Upper CI
N application rate	0 kg/ha/yr	45	0.9	-13.8	14.4
	≤100 kg/ha/yr	77	13.8	8.4	20.1
	100-200 kg/ha/yr	69	13.4	6.8	20.8
	>200 kg/ha/yr	32	8.1	-3.9	20.5
Treatment	BC	42	0.1	-13.7	15.3
	BC+IF	167	14.5	10.5	19.1
	BC+OA	14	7.6	-1.8	20.6
Biochar application rate	≤ 5	81	9.2	3.3	14.9
	5-10	84	18.5	11.2	26.0
	>10	67	0.9	-8.9	10.4
Annual mean temperature	≤10	35	-1.4	-5.8	3.2
	10-20	107	9.5	2.1	16.7
	20-30	90	14.8	7.5	22.7
Climate	Continental and humid-temperate	51	1.4	-2.5	5.2
	Mediterranean	46	2.3	-3.5	7.9
	Tropical and subtropical	127	14.8	7.2	21.8
Soil classification	Entisol & Inceptisol	49	14.6	3.9	26.1
	Alfisol & Cambisol	37	5.9	2.4	9.6
	Ultisol & Oxisol	69	6.5	-3.6	15.8
	Paddy	50	8.0	2.3	14.7
soil pH	≤6.5	177	11.9	6.0	17.6
	>6.5	53	3.1	-1.8	8.0
SOC	≤20 g/kg	184	11.5	6.0	16.6
	>20 g/kg	40	4.1	-4.1	12.2
soil CEC	< 100 $mmol_c/kg$	55	21.0	9.6	31.6
	100-200 $mmol_c/kg$	51	13.3	8.4	18.4
	>200 $mmol_c/kg$	30	15.7	4.5	29.6
Soil texture	Sandy	37	14.2	-2.5	32.2
	Loam	158	9.5	6.4	12.9
	Clay	30	4.0	-7.2	16.5
Pyrolysis temperature	≤400	49	26.5	10.8	40.6
	400-550	76	7.8	4.3	11.4
	550-700	89	2.6	-2.1	7.6
	>700	11	-1.8	-8.8	4.1

Feedstock	Ligneous material	131	1.6	-3.4	6.0
	Cereal residue	75	23.7	15.9	32.7
	Animal and human waste	13	11.2	7.4	15.6
Crop	Maize	70	12.7	1.6	23.7
	Rice	48	8.0	2.1	14.9
	Wheat/barley/oat	55	2.8	-1.6	7.6
	Legumes	17	27.2	8.7	49.5
	Vegetables	17	15.9	1.3	35.9
	Tubers/Bulbs	12	9.3	5.1	13.4
Grand mean		232	9.9	5.3	14.4

Table S4. Proportional changes (mean, and lower and upper confidential intervals) in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) over the control ("non-fertilized" and "fertilized) for soils with different initial soil pH values and application of biochar with different pH values.

	Soil pH	Groups	n	Change (%)	Lower CI	Upper CI
"Non-fertilized control"	≤ 6.5	≤9	46	37.3	13.7	69.3
		>9	31	47.0	23.5	75.2
	> 6.5	≤9	16	39.3	20.6	60.5
		>9	16	7.9	1.4	17.8
"Fertilized control"	≤ 6.5	≤9	68	16.4	8.8	25.5
		>9	72	18.5	12.4	25.3
	> 6.5	≤9	23	11.5	4.2	19.9
		>9	27	-2.2	-8.1	3.7

Table S5. Proportional changes (mean, and lower and upper confidential intervals) in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) at different application rates over the control ("non-fertilized" and "fertilized).

	Groups	n	Change (%)	Lower CI	Upper CI
"Non-fertilized control"	< 20	32	17.7	3.0	38.0
	> 20	30	18.4	0.5	42.6
	Grand mean	62	18.0	5.9	33.0
"Fertilized control"	< 20	56	2.2	-9.5	13.5
	> 20	37	5.1	-11.1	20.1
	Grand mean	93	3.3	-5.5	11.5

Table S6. Proportional changes (mean, and lower and upper confidential intervals) in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) at different time intervals since the start of the experiment over the control (“non-fertilized” and “fertilized).

	Groups	n	Change (%)	Lower CI	Upper CI
"Non-fertilized control"	yr1	20	48.1	20.5	81.6
	yr2	27	105.0	59.2	177.3
	yr3+	22	13.6	-5.4	33.5
	Grand mean	68	55.2	33.4	80.0
"Fertilized control"	yr1	59	0.4	-10.6	10.4
	yr2	67	0.4	-16.9	21.1
	yr3+	44	30.5	16.6	48.5
	Grand mean	170	7.2	-0.8	15.2

Table S7. Proportional changes (mean, and lower and upper confidential intervals) in crop yield of the "fertilized control" for each level of the individual categories over the "non-fertilized control".

Category	Groups	n	Change (%)	Lower CI	Upper CI
Soil classification	Entisol & Inceptisol	19	82.9	37.3	133.6
	Alfisol & Cambisol	21	33.4	20.7	46.9
	Ultisol & Oxisol	35	45.9	28.4	65.4
	Paddy	37	3.5	-6.3	17.8
soil pH	≤6.5	97	30.7	17.1	46.3
	>6.5	21	24.8	12.7	39.0
soil CEC	≤100 $mmol_c/kg$	11	111.3	58.7	173.1
	100 – 200 $mmol_c/kg$	22	-9.0	-15.8	-3.1
	>200 $mmol_c/kg$	21	6.4	-7.3	26.3
Soil texture	Sand	17	102.7	60.0	152.6
	Loam	81	10.0	3.7	17.2
	Clay	20	33.7	10.0	69.5
Crop	Maize	29	90.6	57.1	127.9
	Wheat/barley/oat	42	35.9	21.2	54.4
	Rice	35	-4.7	-8.2	-1.0
Grand mean		118	29.8	18.9	42.7
Grand mean when only considering IF in the "fertilized control"		106	26.3	14.9	39.7

Table S8. Proportional changes (mean, and lower and upper confidential intervals) in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment), excluding rice crops, for each level of the individual categories over the "non-fertilized control".

Category	Groups	n	Change (%)	Lower CI	Upper CI
N application rate	0 kg/ha/yr	38	11.3	1.6	22.6
	≤100 kg/ha/yr	31	36.4	24.3	50.8
	100-200 kg/ha/yr	20	145.2	90.9	208.1
Treatment	BC	38	11.3	1.5	23.3
	BC+IF	59	58.8	34.2	90.4
Biochar application rate	≤ 5	52	47.6	23.3	77.8
	5-10	33	32.6	20.2	51.2
	>10	22	25.4	6.6	47.9
Annual mean temperature	≤10	20	2.0	-5.6	10.6
	10-20	47	41.0	23.8	62.2
	20-30	40	56.6	30.0	90.6
Climate	Continental and humid-temperate	35	16.3	7.2	28.6
	Mediterranean	43	23.3	12.4	37.0
	Tropical and subtropical	29	105.4	55.4	161.8
Soil classification	Entisol & Inceptisol	23	75.1	28.7	144.0
	Alfisol & Cambisol	33	18.2	7.0	32.7
	Ultisol & Oxisol	37	46.6	25.5	69.6
soil pH	≤6.5	72	57.3	35.7	82.2
	>6.5	33	18.8	7.9	32.3
SOC	≤20 g/kg	89	47.5	29.3	69.5
	>20 g/kg	11	10.3	-2.3	28.9
soil CEC	≤100 $mmol_c/kg$	11	171.7	91.2	265.6
	>200 $mmol_c/kg$	10	26.6	20.7	32.3
Soil texture	Sandy	17	108.4	42.9	180.7
	Loam	80	18.6	11.3	26.6
	Clay	10	129.5	72.9	199.6

Pyrolysis temperature	≤400	21	97.4	37.0	158.4
	400-550	31	25.4	10.0	48.8
	550-700	55	25.5	15.7	37.5
Feedstock	Papermill residue	11	10.1	-5.7	23.0
	Ligneous material	65	23.8	14.6	35.8
	Cereal residue	25	116.2	67.4	173.5
Crop	Maize	30	95.5	49.6	145.7
	Wheat/barley/oat	49	29.2	16.7	47.5
	Rapeseed/sunflowers	10	13.1	-17.6	55.3
Grand mean		107	37.7	23.9	54.2

Table S9. Proportional changes (mean, and lower and upper confidential intervals) in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment), excluding rice crops, for each level of the individual categories over the "fertilized control".

Category	Groups	n	Change (%)	Lower CI	Upper CI
N application rate	0 kg/ha/yr	28	1.4	-19.7	23.8
	≤100 kg/ha/yr	61	12.3	5.8	20.1
	100-200 kg/ha/yr	63	14.4	7.4	21.7
	>200 kg/ha/yr	23	8.3	-6.4	25.3
Treatment	BC	26	1.3	-22.6	26.6
	BC+IF	135	14.7	9.9	19.7
	BC+OA	14	7.6	-2.8	20.1
Biochar application rate	≤ 5	68	10.2	3.7	16.7
	5-10	67	18.4	10.4	28.2
	>10	49	0.6	-12.3	13.3
Annual mean temperature	≤10	34	-1.4	-5.9	2.9
	10-20	87	11.1	2.5	19.1
	20-30	63	16.0	6.5	25.2
Climate	Continental and Humid-temperate	50	0.1	-3.5	3.8
	Mediterranean	46	2.3	-3.1	7.8
	Tropical and Subtropical	80	18.5	8.1	29.2
Soil classification	Entisol & Inceptisol	49	14.9	4.5	26.7
	Alfisol & Cambisol	37	5.9	2.4	9.5
	Ultisol & Oxisol	69	6.5	-3.5	15.9
soil pH	≤6.5	133	13.8	7.1	20.6
	>6.5	49	0.7	-3.4	4.9
SOC	≤20 g/kg	150	12.1	5.5	18.4
	>20 g/kg	26	3.7	-7.2	16.3
soil CEC	≤ 100 $mmol_c/kg$	51	22.5	9.6	34.3
	100-200 $mmol_c/kg$	34	11.3	5.5	17.4
	>200 $mmol_c/kg$	16	26.2	7.8	50.9
Soil texture	Sandy	36	14.4	-5.2	32.8

	Loam	123	9.7	5.9	13.3
	Clay	18	1.8	-13.1	17.4
Pyrolysis temperature	≤400	49	26.5	10.4	41.5
	400-550	63	9.3	4.8	13.9
	550-700	57	-2.2	-8.5	3.8
	>700	11	-1.8	-8.7	4.3
Feedstock	Ligneous material	103	-1.4	-7.8	4.3
	Cereal residue	55	30.4	20.2	40.8
	Animal and human waste	13	11.2	7.6	15.6
Crop	Maize	70	12.7	2.2	22.6
	Wheat/barley/oat	55	2.8	-1.9	7.0
	Legumes	17	27.2	9.1	48.3
	Vegetables	17	15.9	2.5	36.0
	Tubers/Bulbs	12	9.3	5.2	13.6
Grand mean		184	10.5	4.8	15.5

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