Supplementary Online Material

Characterization of biochars to evaluate recalcitrance and agronomic performance

Akio Enders[a], Kelly Hanley[a], Thea Whitman[a], Stephen Joseph[b], Johannes Lehmann[a]*

[a]Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853, United States

[b]School of Material Science and Engineering, University of New South Wales, 2052, Sydney, Australia

*Corresponding author. Tel.: +1 607 254 1236

E-mail addresses: ae55@cornell.edu (A. Enders), klh54@cornell.edu (K. Hanley), tlw59@cornell.edu (T. Whitman), s.joseph@unsw.edu.au (S. Joseph), CL273@cornell.edu (Johannes Lehmann).

Supplementary Methods

Proximate analysis

The hygroscopic nature of certain biochars necessitated the use of individual dessicators to cool each sample separately prior to weighing. Dessicators were prepared by placing approximately 50 mL of 6 mesh anhydrous calcium sulfate (#12001, Drierite Co. Ltd., Xenia, OH) into pint size canning jars (#66000 Hearthmark, LLC dba Jarden Home Brands, Daleville, IN) each fitted with a 50-mL beaker (#1000-50, Corning Incorporated Life Sciences Lowell, MA) to hold crucibles above the dessicant. Porcelain crucibles, 43 mm in diameter and 37mm tall (#60107, CoorsTek, Inc., Golden, CO) and 45mm I.D. crucible covers (#60124, CoorsTek, Inc., Golden, CO) were utilized for moisture, volatiles, and ash determinations. Crucibles and covers were prepared by heating from 105°C to 750°C at 5°C /min, maintaining temperature at 750°C for 10 min, and cooling to 105°C prior to transfer to dessicators. A muffle furnace equipped with a PID controller was used for all analyses (Barnstead Thermolyne F6020C-33-60-80, Barnstead International, Dubuque, IA). Temperature control PID values were tuned for each temperature and ventilation combination to enhance accuracy.

Moisture determination was the initial step prior to both volatiles and ash determination. Each sample consisted of 1.0050 g +/- 0.0050 g and was processed in duplicate. Samples were weighed into crucibles with covers and placed into a furnace preheated to 105°C. An inert environment was created to prevent O chemisorption and therefore weight gain during moisture determination (Bradbury and Shafidazeh 1980). This was achieved by capping the furnace ventilation port and charging with 1.2 L/min of Ar gas, equivalent to 5 exchanges per hour. Even then, it was not possible to achieve the +/- <0.5 mg constant weight between drying intervals required by the ASTM method, therefore moisture content was defined as weight loss resulting from 18 hours at 105°C according to the following:

$$Moisture\ \% = \frac{weight_{air\,dried} - weight_{105°C\,dried}}{weight_{air\,dried}} \times 100$$

To determine volatile matter, the furnace was then preheated to 950°C with the vent port capped, but without argon charge. It was impossible to maintain furnace temperature with the door open, and so necessitated another modification to the ASTM method. Samples were introduced into the furnace as quickly as possible, rather than preheating crucibles by placing them on the outer ledge of the furnace for 2 min, then on the edge of the furnace for 3 min, as described in the ASTM method. Furthermore, a set of 24 crucibles was utilized for all volatiles determinations to encourage more consistent reheating across runs. It should be noted that the furnace temperature would not rebound to 950°C until approximately 8 min after the samples had been introduced. Samples were removed from the furnace after 10 min and placed on a refractory brick to cool until they could be safely transferred into dessicators, at a point above 200°C. Covered crucibles were weighed after cooling to ambient temperature and volatile matter content was calculated as follows:

$$Volatile\ matter\ \% = \frac{weight_{105°C\,dried} - weight_{950°C\,devolatilized}}{weight_{105°C\,dried}} \times 100$$

For determination of ash contents, covers were removed from the crucibles and the furnace vent port was connected to the fume hood exhaust. Following this, samples were placed in the furnace and the temperature was increased from 105°C to 750°C at 5°C/min, and then held at 750°C for 6 hours. The furnace was allowed to cool to 105°C before samples were transferred to dessicators. Ash content was determined by weight loss according to the following:

$$Ash\ \% = \frac{weight_{residue\ after\ 750°C}}{weight_{105°C\ dried}} \times 100$$

Volatile and ash contents were used to calculate the fixed carbon content according to the following:

$$Fixed\ carbon\ \% = \frac{weight_{105°C\ dried} - weight_{950°C\ devolatilized} - weight_{residue\ after\ 750°C}}{weight_{105°C\ dried}} \times 100$$

It should be noted that the so-called fixed carbon content is given as the mass residue, and is not strictly a C content. All analyses were done in duplicate.

Lower-temperature volatile determination

For determination of lower-temperature (LT) volatiles, the furnace was preheated to 105°C with the inert gas environment as mentioned above. Samples in covered crucibles were placed into the furnace and the temperature was increased by 5°C/min to 350°C, where it was held for 2 hours. Because the active ventilation necessary to cool the furnace at a reasonable rate would interfere with the anoxic environment, samples were removed from the furnace at 350°C and quickly placed into individual dessicators. Covered crucibles were weighed after cooling to ambient temperature and LT volatiles content was calculated according to the following:

$$LT\ volatile\ matter\ \% = \frac{weight_{105°C\ dried} - weight_{350°C\ devolatilized}}{weight_{105°C\ dried}} \times 100$$

Cation exchange capacity

Air dry biochars were sieved to 0.5-2.0 mm prior to analysis for exchangeable cations and CEC. The method used was modeled after Sumner and Miller (1996). Briefly, 1.00 +/- 0.05 g of biochar was added to 40 mL of pH 7.0 buffered NH_4-OAc and shaken overnight in 60 mL glass vials. Contents were transferred using an additional 10 mL NH_4-OAc into extractor syringes prepared with 0.7 +/_0.3 g of filter pulp (Schleicher and Schuell Microscience, Dassel, Germany). Syringes were mounted in a mechanical vacuum extractor (model 24-01, Concept Engineering, Lincoln, NE), used to extract a total of 50 mL NH_4-OAc solution over approximately 2 h. An additional 40 mL of NH_4-OAc was added to the sample syringes and extracted a second time. The two extractions were pooled and brought to 100 mL volume with NH_4-OAc. A 20-mL subsample of extract was processed further in a porcelain evaporating dish on a hotplate set to 250°C. Organic matter was decomposed by adding 2.0 mL of 35% HNO_3 and 5.0 mL of 15% H_2O_2 and evaporated to dryness. Silicates were dehydrated by subsequently adding 3.0 mL of 38% HCl, evaporating to dryness, and heating for an additional 1 h. Finally, 10 mL of 3.8% HCl was added to solublize ash and solutions were analyzed for cations using ICP (model ICAP 61E trace analyzer, Thermo Electron, Waltham, Ma). Exchangable cations were calculated as follows:

$$cation\ (mmol_c / kg) = \frac{cation\,(mg/L) \times extract\ (mL) \times cation\,valence \times ICP\,sample\,(mL)}{biochar\,(g) \times cation\ (g/mol) \times subsample\,(mL) \times}$$

CEC was determined by adding 60 mL of 95% EtOH to the sample syringes to remove NH_4-OAc not adsorbed to exchange sites. Following this, 50.0 mL of 2 M KCl was added and left overnight to displace NH_4. Samples were then extracted over 2 h and an additional 40 mL of 2 M KCl was added to the sample syringes and extracted a second time. The two extractions were pooled and brought to 100 mL volume with 2 M KCl. Ammonium was quantified in the extracts using flow analysis (Technicon AutoAnalyzer with CEC manifold and 440nm filter, model 1, Technicon Instrument Corp. Tarrytown, NY). CEC was calculated according to the following:

$$CEC\ mmol_c / kg = \frac{NH_4\, concentration\,(mg/L) \times total\ extract\,(mL)}{biochar\,(g) \times NH_4\,(g/mol)}$$

Supplementary Table S1. Production details of biochars utilized in this study.

Label in figures	Feedstock	Production temperatures (°C)	Thermal production condition	Reference
Bull Manure	Bull manure with sawdust	300, 350, 400, 450, 500, 550, 600	Slow pyrolysis[a]	Main manuscript
Corn	Corn stover	300, 350, 400, 450, 500, 550, 600	Slow pyrolysis[a]	Main manuscript
Dairy Manure	Dairy manure with rice husks	300, 350, 400, 450, 500, 550, 600	Slow pyrolysis[a]	Main manuscript
Hazelnut	Hazelnut shells	300, 350, 400, 450, 500, 550, 600	Slow pyrolysis[a]	Main manuscript
Oak	Oak wood	300, 350, 400, 450, 500, 550, 600	Slow pyrolysis[a]	Main manuscript
Pine	Pine wood	300, 350, 400, 450, 500, 550, 600	Slow pyrolysis[a]	Main manuscript
Poultry Manure	Poultry manure with sawdust	300, 350, 400, 450, 500, 550, 600	Slow pyrolysis[a]	Main manuscript
Raw Dairy Manure	Dairy manure	500	Slow pyrolysis[a]	Main manuscript
Digested Dairy Manure	Anaerobically digested dairy manure	300, 350, 400, 450, 500, 550, 600	Slow pyrolysis[a]	Main manuscript
Composted Dairy Manure	Composted, dewatered, anaerobically digested dairy manure	500	Slow pyrolysis[a]	Main manuscript

Composted Dairy Manure + Wood	Composted, dewatered, anaerobically digested dairy manure with chipped pallets	500	Slow pyrolysis[a]	Main manuscript
Mixed Woodchips	Chipped pallets	500	Slow pyrolysis[a]	Main manuscript
Grass Clippings	Summer yard waste, mainly grass	500	Slow pyrolysis[a]	Main manuscript
Leaves	Yard waste collected in Fall, mainly leaves	500	Slow pyrolysis[a]	Main manuscript
Brush	Winter yard waste, mainly brush	500	Slow pyrolysis[a]	Main manuscript
Food	Food waste	300, 400, 500, 600	Slow pyrolysis[a]	Main manuscript
Paper	Paper mill waste	300, 400, 500, 600	Slow pyrolysis[a]	Main manuscript
Mixture	Poultry manure, sawdust, bentonite and kaolinite, crushed brick, cement kiln residue, blood and bone	220, 240	Torrefaction, batch reactor, 8 hour residence time, 2 kg per batch	Stephen Joseph, Chee Chia (University of New South Wales)
Corn 2	Corn stover	600	Slow pyrolysis	Best Energies Australia
Carbonized Pine	Wood or nut shells	700-750 for 1 min; 300-550 for 10 min	Updraft pyrolysis, 250 kg/h capacity	BEC (2011)
Soybean	Soybean crop residue, stalks	500	Fast pyrolysis, fluidized bed, 1 s residence time, 0.2 s contact time in bed, 5 kg/h capacity	Boateng et al (2010)

Switchgrass	Switchgrass	500	Fast pyrolysis, fluidized bed, 1 s residence time, 0.2 s contact time in bed, 5 kg/h capacity	Boateng 2007
Switchgrass 2	Switchgrass	500	Fast/intermediate pyrolysis, auger, 15-30 s contact time, 30 kg/h capacity	Sergio Capareda (Texas A&M University)
Pine 2	Pine wood chips	500	Fast/intermediate pyrolysis, auger, 15-30 s contact time, 30 kg/h capacity	Sergio Capareda (Texas A&M University)
Mixed Softwood	Mixed hardwood	450-500	Fast pyrolysis, bubbling fluidized bed, <5 s contact time	Dynamotive
Mixed Vegetation	Unidentified vegetative material	450-500	Fast pyrolysis, bubbling fluidized bed, <5 s contact time	Dynamotive
Mixed Hardwood	Mixed hardwood chips	450-500	Fast pyrolysis, bubbling fluidized bed, <5 s contact time	Dynamotive
Poultry 2	Poultry manure and carcasses	300-600	Fixed-bed gasification, 30-60 min contact time, 300 kg/h capacity	Josh Frye, Lehmann and Joseph (2009)
Kuikui	Kuikui nut shells	400-500	Flash pyrolysis, 1.1 MPa pressure, batch reactor, appr. 0.5-2 h pyrolysis time, appr 1 kg capacity	Antal et al. (2003)
Macadamia	Macademia nut shells	400-500	Flash pyrolysis, 1.1 MPa pressure, batch reactor, appr. 0.5-2 h pyrolysis time, appr 1 kg capacity	Antal et al. (2003)
Rice Husk	Rice husks	800	Gasification, 200 kg/h capacity	Jerome Matthews (Phillipine Rice Research Institute)
Grass Clippings 2	Golf course grass clippings		Slow pyrolysis	Main manuscript

Corn 3	Corn stover	515	Ablative-updraft pyrolysis, continuous feed, 10 min contact time, 19kg/h capacity	Das et al. (2009)
Peanut	Peanut shells	480	Ablative-updraft pyrolysis, continuous feed, 10 min contact time, 19kg/h capacity	Das et al. (2009)

Supplementary Table S2. Proximate analysis of biochars and selected feedstocks according to a modified ASTM D1762-84, as stated in Supplementary Methods.

Biochar	Volatile Matter	Ash	Fixed Carbon	Reference
		%w/w		
Soybean	47.0	15.2	37.8	Main manuscript
Switchgrass	35.1	41.2	23.7	Main manuscript
Bull Manure 300[a]	55.5	7.7	36.8	Main manuscript
Bull Manure 350	58.7	8.3	33.0	Main manuscript
Bull Manure 400	37.0	9.4	53.7	Main manuscript
Bull Manure 450	46.2	9.3	44.5	Main manuscript
Bull Manure 500	30.5	10.4	59.2	Main manuscript
Bull Manure 550	39.0	10.9	50.1	Main manuscript
Bull Manure 600	30.0	10.6	59.4	Main manuscript
Rice Husk	23.2	60.8	16.0	Main manuscript
Carbonized Pine	18.7	4.0	77.4	Main manuscript
Composted Dairy Manure	33.0	50.1	16.9	Main manuscript
Composted Dairy Manure + Wood	25.7	58.5	15.8	Main manuscript
Corn 300	51.9	10.7	37.4	Main manuscript
Corn 350	48.9	11.4	39.8	Main manuscript
Corn 400	44.7	12.9	42.4	Main manuscript
Corn 450	42.7	12.5	44.9	Main manuscript
Corn 500	31.1	17.6	51.3	Main manuscript
Corn 550	37.3	14.0	48.7	Main manuscript
Corn 600	23.5	16.7	59.8	Main manuscript

Dairy Manure 300	45.4	10.1	44.5	Main manuscript
Dairy Manure 350	58.4	10.2	31.4	Main manuscript
Dairy Manure 400	39.1	11.5	49.5	Main manuscript
Dairy Manure 450	42.1	11.7	46.2	Main manuscript
Dairy Manure 500	33.9	12.4	53.7	Main manuscript
Dairy Manure 550	41.8	13.4	44.7	Main manuscript
Dairy Manure 600	30.7	12.6	56.6	Main manuscript
Digested Dairy Manure 300	57.6	39.2	3.2	Main manuscript
Digested Dairy Manure 350	55.6	12.7	31.7	Main manuscript
Digested Dairy Manure 400	58.6	14.5	26.9	Main manuscript
Digested Dairy Manure 450	41.5	17.8	40.8	Main manuscript
Digested Dairy Manure 500	42.7	14.7	42.6	Main manuscript
Digested Dairy Manure 550	41.8	17.3	41.0	Main manuscript
Digested Dairy Manure 600	39.4	18.8	41.7	Main manuscript
Mixed Softwood	45.5	5.6	48.9	Main manuscript
Peanut	45.6	6.8	47.6	Main manuscript
Food 300	45.4	23.3	31.3	Main manuscript
Food 400	35.7	46.0	18.3	Main manuscript
Food 500	33.7	52.7	13.6	Main manuscript
Food 600	34.5	52.0	13.6	Main manuscript
Poultry 2	37.7	58.4	3.9	Main manuscript
Hazelnut 300	48.8	2.0	49.2	Main manuscript
Hazelnut 350	56.1	1.2	42.7	Main manuscript

Hazelnut 400	43.5	1.7	54.8	Main manuscript
Hazelnut 450	47.0	1.3	51.7	Main manuscript
Hazelnut 500	37.2	1.9	60.9	Main manuscript
Hazelnut 550	41.7	1.4	56.9	Main manuscript
Hazelnut 600	29.6	2.2	68.2	Main manuscript
Corn 3	28.3	-[b]	-	Main manuscript
Grass Clippings 2	23.5	8.8	67.7	Main manuscript
Mixed Vegetation	31.6	38.6	29.9	Main manuscript
Kuikui	58.3	2.7	39.0	Main manuscript
Macadamia	70.0	0.7	29.3	Main manuscript
Corn 2	25.7	64.2	10.1	Main manuscript
Oak 300	61.1	0.3	38.5	Main manuscript
Oak 350	60.8	1.1	38.1	Main manuscript
Oak 400	40.9	0.8	58.3	Main manuscript
Oak 450	44.4	0.6	55.0	Main manuscript
Oak 500	30.7	3.7	65.6	Main manuscript
Oak 550	38.5	0.6	60.9	Main manuscript
Oak 600	27.5	1.3	71.2	Main manuscript
Paper 300	50.1	50.7	-0.8	Main manuscript
Paper 400	44.2	54.6	1.2	Main manuscript
Paper 500	42.5	57.4	0.0	Main manuscript
Paper 600	41.1	59.1	-0.2	Main manuscript
Pine 300	55.3	1.5	43.2	Main manuscript

Pine 350	56.3	0.6	43.2	Main manuscript
Pine 400	45.5	1.1	53.5	Main manuscript
Pine 450	48.8	1.5	49.7	Main manuscript
Pine 500	37.0	1.0	62.0	Main manuscript
Pine 550	40.2	0.8	59.0	Main manuscript
Pine 600	27.7	1.1	71.2	Main manuscript
Poultry Manure 300	46.8	46.7	6.5	Main manuscript
Poultry Manure 350	47.2	51.2	1.6	Main manuscript
Poultry Manure 400	43.8	51.7	4.5	Main manuscript
Poultry Manure 450	46.2	53.6	0.2	Main manuscript
Poultry Manure 500	43.2	52.6	4.2	Main manuscript
Poultry Manure 550	44.6	54.9	0.6	Main manuscript
Poultry Manure 600	44.4	55.8	-0.2	Main manuscript
Raw Dairy Manure	33.0	32.0	35.0	Main manuscript
Mixture 220	37.7	53.6	8.8	Main manuscript
Mixture 240	26.8	70.1	3.1	Main manuscript
Switchgrass 2	27.7	16.5	55.8	Main manuscript
Pine 2	46.8	46.7	6.5	Main manuscript
Mixed Hardwood	56.8	4.3	38.9	Main manuscript
Mixed Woodchips	26.9	10.9	62.1	Main manuscript
Leaves	40.3	14.5	45.2	Main manuscript
Grass Clippings	38.4	25.5	59.8	Main manuscript
Brush	40.1	1.8	58.2	Main manuscript

Bull Manure feedstock	84.4	5.3	10.2	Main manuscript
Corn feedstock	85.2	9.0	5.8	Main manuscript
Dairy Manure feedstock	80.9	5.6	13.5	Main manuscript
Hazelnut feedstock	82.4	2.7	15.0	Main manuscript
Oak feedstock	88.6	2.0	9.4	Main manuscript
Pine feedstock	89.8	1.8	8.3	Main manuscript
Poultry Manure feedstock	60.5	36.3	3.1	Main manuscript
Switchgrass FP [3] 500	28.4	25.9	42.0	Brewer et al. 2009
Corn stover FP 500	14.9	49.7	34.4	Brewer et al. 2009
Corn stover gasification 730	5.5	54.0	38.5	Brewer et al. 2009
Corn stover SP 500	11.1	32.4	54.7	Brewer et al. 2009
Hardwood SP n/a	19.7	13.9	63.8	Brewer et al. 2009
Switchgrass FP 500	16.4	54.6	26.4	Brewer et al. 2009
Switchgrass gasification 760	10.3	53.0	34.3	Brewer et al. 2009
Switchgrass SP 500	7.1	52.5	39.5	Brewer et al. 2009
Almond shells 600	9.8	3.7	86.5	Cordero et al. 2001
Eucalyptus saligna 700	6.6	1.9	91.5	Cordero et al. 2001
Olive stones 600	11.3	6.6	82.1	Cordero et al. 2001
Pinus halepensis 300	68.1	0.6	31.3	Cordero et al. 2001
Pinus halepensis 350	49.5	1.2	49.4	Cordero et al. 2001
Pinus halepensis 400	36.5	1.3	62.2	Cordero et al. 2001
Pinus halepensis 450	27.4	1.4	71.2	Cordero et al. 2001
Pinus halepensis 500	20.2	1.7	78.1	Cordero et al. 2001

Pinus halepensis 550	18.1	1.7	80.2	Cordero et al. 2001
Pinus halepensis 600	13.4	1.7	84.9	Cordero et al. 2001
Quercus rotundifolia 300	65.1	1.5	33.4	Cordero et al. 2001
Quercus rotundifolia 350	43.4	1.3	55.3	Cordero et al. 2001
Quercus rotundifolia 400	34.5	1.3	64.2	Cordero et al. 2001
Quercus rotundifolia 450	21.8	1.8	76.4	Cordero et al. 2001
Quercus rotundifolia 500	17.5	2.8	79.7	Cordero et al. 2001
Quercus rotundifolia 550	14.7	3.1	82.2	Cordero et al. 2001
Quercus rotundifolia 600	13.2	3.2	83.6	Cordero et al. 2001
Wet straw 600	11.8	24.7	63.5	Cordero et al. 2001
High Volatile Matter' n/a	22.5	3.3	74.2	Deenick et al. 2010
Low Volatile Matter' n/a	6.3	41.8	51.9	Deenick et al. 2010
Corn stover 450	12.7	28.7	58.0	Lee et al. 2010
Corn stover 700	7.6	32.6	58.8	Lee et al. 2010
Apricot stone 823	19.8	8.5	71.7	Özçimen and Ersoy-Mericboyu 2010
Chestnut shell 750	34.3	5.4	60.3	Özçimen and Ersoy-Mericboyu 2010
Grapeseed 750	39.5	9.6	51.0	Özçimen and Ersoy-Mericboyu 2010
Hazelnut shell 750	30.3	6.6	63.2	Özçimen and Ersoy-Mericboyu 2010
Rapeseed 550	13.6	21.8	64.6	Özçimen and Karaosmanoğlu 2004
Rapeseed cake 500	18.7	17.6	63.7	Özçimen and Karaosmanoğlu 2004
Sunflower 550	13.4	28.9	57.7	Sanchez et al. 2009
Aspidosperma australe 350	66.8	1.9	29.3	Spokas 2010
Aspidosperma australe 850	8.1	7.2	80.2	Spokas 2010

Aspidosperma quebracho 'Blanco Schlecht' 350	69.5	0.9	26.9	Spokas 2010
Aspidosperma quebracho 'Blanco Schlecht' 850	14.6	4.3	79.2	Spokas 2010
Grape bagasse NA	20.6	14.0	65.4	Spokas 2010
Hardwood sawdust 500	29.0	15.0	55.0	Spokas 2010
Macadamia nut shell 600	17.0	2.0	81.0	Spokas 2010
Mixed wood chip 550	33.6	4.8	58.5	Spokas 2010
Olive bagasse NA	16.2	16.1	67.7	Spokas 2010
Ponderosa pine 100	77.1	1.2	21.7	Spokas 2010
Ponderosa pine 200	77.1	1.5	21.4	Spokas 2010
Ponderosa pine 300	70.3	1.5	28.2	Spokas 2010
Ponderosa pine 400	36.4	1.4	62.2	Spokas 2010
Ponderosa pine 500	25.2	2.1	72.7	Spokas 2010
Ponderosa pine 600	11.1	3.7	85.2	Spokas 2010
Ponderosa pine 700	6.3	1.7	92.0	Spokas 2010
Rapeseed plant 400	27.1	12.2	60.7	Spokas 2010
Rapeseed plant 500	17.5	12.9	69.6	Spokas 2010
Rapeseed plant 500	18.7	17.6	63.7	Spokas 2010
Rapeseed plant 600	11.5	13.9	74.7	Spokas 2010
Rapeseed plant 700	9.0	14.4	76.7	Spokas 2010
Rapeseed plant 800	8.0	15.3	79.9	Spokas 2010
Rapeseed plant 900	3.6	16.1	80.3	Spokas 2010
Tall fescue 100	69.6	6.9	23.5	Spokas 2010
Tall fescue 200	70.7	5.7	23.6	Spokas 2010

Tall fescue 300	54.4	9.4	36.2	Spokas 2010
Tall fescue 400	26.8	16.3	56.9	Spokas 2010
Tall fescue 500	20.3	15.4	64.3	Spokas 2010
Tall fescue 600	13.5	18.9	67.6	Spokas 2010
Tall fescue 700	9.1	19.3	71.6	Spokas 2010
Wood pellets 400–600	12.0	6.0	76.8	Spokas 2010
Bubinga 250	66.4	0.9	32.7	Zimmerman 2010
Bubinga 400	41.1	1.8	57.1	Zimmerman 2010
Bubinga 525	35.0	1.2	63.8	Zimmerman 2010
Bubinga 650	22.3	1.3	76.4	Zimmerman 2010
Eastern Red Cedar 250	62.6	0.9	36.5	Zimmerman 2010
Eastern Red Cedar 400	52.0	0.4	47.6	Zimmerman 2010
Eastern Red Cedar 525	39.1	1.3	59.6	Zimmerman 2010
Eastern Red Cedar 650	30.9	1.0	68.1	Zimmerman 2010
Loblolly Pine 250	61.1	0.3	38.6	Zimmerman 2010
Loblolly Pine 400	58.6	0.5	40.9	Zimmerman 2010
Loblolly Pine 525	25.7	1.2	73.1	Zimmerman 2010
Loblolly Pine 650	25.2	1.1	73.7	Zimmerman 2010
Loblolly Pine 72 h 400	51.2	0.9	47.9	Zimmerman 2010
Loblolly Pine 72 h 650	21.7	1.2	77.1	Zimmerman 2010
Laurel Oak 250	66.0	1.4	32.6	Zimmerman 2010
Laurel Oak 400	51.9	2.6	45.5	Zimmerman 2010
Laurel Oak 525	36.4	6.8	56.8	Zimmerman 2010

Laurel Oak 650	20.7	3.7	75.6	Zimmerman 2010
Laurel Oak 72h 400	41.9	5.2	52.9	Zimmerman 2010
Laurel Oak 72h 650	14.7	7.4	77.9	Zimmerman 2010
Sugar cane bagasse 250	71.8	9.5	18.7	Zimmerman 2010
Sugar cane bagasse 400	63.9	2.7	33.4	Zimmerman 2010
Sugar cane bagasse 525	55.1	8.7	36.2	Zimmerman 2010
Sugar cane bagasse 650	48.8	6.8	44.4	Zimmerman 2010
Eastern Gamma Grass 250	62.5	6.8	30.7	Zimmerman 2010
Eastern Gamma Grass 400	51.4	13.2	35.4	Zimmerman 2010
Eastern Gamma Grass 525	36.7	24.8	38.5	Zimmerman 2010
Eastern Gamma Grass 650	33.0	15.9	51.1	Zimmerman 2010

[a] Values refer to pyrolysis temperature; where no temperature is indicated, information is included in Supplementary Table S1

[b] data not available

Supplementary Table S3. Ultimate analysis of selected biochars and feedstocks, as stated in main manuscript.

Biochar	C_{tot}	C_{inorg} [% of C_{tot}]	C_{org} [% of C_{tot}]	O_{tot}	H	N
			(%w/w)			
Soybean	-	-	-	-	-	-
Switchgrass	-	-	-	-	-	-
Bull Manure 300	60.6	0 [0]	60.6 [100]	26.6	4.9	1.3
Bull Manure 350	66.3	0 [0]	66.3 [100]	23.8	4.0	1.3
Bull Manure 400	68.5	0.6 [0.9]	67.9 [99.1]	17.4	3.5	1.2
Bull Manure 450	71.5	0 [0]	71.5 [100]	15.6	3.3	1.1
Bull Manure 500	74.1	0 [0]	74.1 [100]	17.4	2.6	1.1
Bull Manure 550	74.3	0 [0]	74.3 [100]	13.4	2.3	1.1
Bull Manure 600	76.0	0 [0]	76 [100]	14.3	1.8	0.8
Rice Husk	-	-	-	-	-	-
Carbonized Pine	-	-	-	-	-	-
Composted Dairy Manure	37.8	-	-	-	-	2.0
Composted Dairy Manure + Wood	74.0	-	-	-	-	0.6
Corn 300	59.9	0 [0]	59.9 [100]	24.8	4.5	1.1
Corn 350	65.2	0 [0]	65.2 [100]	23.2	3.8	1.2
Corn 400	65.2	0 [0]	65.2 [100]	20.1	3.3	1.1
Corn 450	68.3	0 [0]	68.3 [100]	16.4	2.7	1.1
Corn 500	70.3	0 [0]	70.3 [100]	10.7	1.9	1.1

Corn 550	72.2	0 [0]	72.2 [100]	12.3	2.3	1.0
Corn 600	70.7	1.9 [2.8]	68.7 [97.2]	9.3	2.3	1.1
Dairy Manure 300	61.5	0 [0]	61.5 [100]	22.6	4.5	1.6
Dairy Manure 350	64.1	0.9 [1.4]	63.2 [98.6]	19.8	4.1	1.8
Dairy Manure 400	67.1	1.1 [1.6]	66 [98.4]	16.8	3.3	1.4
Dairy Manure 450	70.1	1 [1.4]	69.1 [98.6]	13.6	3.1	1.5
Dairy Manure 500	72.5	0 [0]	72.5 [100]	12.9	2.6	1.4
Dairy Manure 550	72.3	0.9 [1.3]	71.4 [98.7]	10.4	2.3	1.5
Dairy Manure 600	75.2	0 [0]	75.2 [100]	11.6	2.0	1.3
Digested Dairy Manure 300	56.1	-	-	-	-	2.7
Digested Dairy Manure 350	57.7	-	-	-	-	2.4
Digested Dairy Manure 400	63.8	-	-	-	-	2.4
Digested Dairy Manure 450	60.4	-	-	-	-	2.5
Digested Dairy Manure 500	59.4	-	-	-	-	2.6
Digested Dairy Manure 550	60.9	-	-	-	-	2.2
Digested Dairy Manure 600	62.8	-	-	-	-	2.2
Mixed Softwood	-	-	-	-	-	-
Peanut	-	-	-	-	-	-
Food 300	65.3	11.7 [17.9]	53.6 [82.1]	-	-	5.3
Food 400	52.4	13.2 [25.2]	39.2 [74.8]	-	-	3.4
Food 500	42.0	0 [0]	42 [100]	-	-	2.8

Food 600	32.0	0 [0]	32 [100]	-	-	1.2
Poultry 2	-	-	-	-	-	-
Hazelnut 300	69.9	0 [0]	69.9 [100]	23.7	3.9	0.5
Hazelnut 350	73.1	0 [0]	73.1 [100]	23.3	3.7	0.5
Hazelnut 400	77.2	0 [0]	77.2 [100]	18.7	3.3	0.5
Corn 3	-	-	-	-	-	-
Hazelnut 450	79.4	0 [0]	79.4 [100]	16.8	2.9	0.5
Grass Clippings 2	-	-	-	-	-	-
Hazelnut 500	80.6	0 [0]	80.6 [100]	14.5	3.0	0.5
Hazelnut 550	84.6	0 [0]	84.6 [100]	11.5	2.7	0.5
Mixed Vegetation	-	-	-	-	-	-
Hazelnut 600	87.9	0 [0]	87.9 [100]	10.9	2.3	0.5
Kuikui	-	-	-	-	-	-
Macadamia	-	-	-	-	-	-
Corn 2	29.1	-	-	-	-	0.3
Oak 300	63.9	0 [0]	63.9 [100]	30.8	4.8	0.1
Oak 350	74.9	0.1 [0.1]	74.8 [99.9]	20.4	3.4	0.2
Oak 400	78.8	3.3 [4.1]	75.5 [95.9]	17.1	3.2	0.2
Oak 450	85.1	1.3 [1.5]	83.7 [98.5]	11.2	3.0	0.2
Oak 500	85.3	0 [0]	85.3 [100]	9.6	2.6	0.2
Oak 550	87.9	0 [0]	87.9 [100]	9.0	2.4	0.2

Oak 600	87.6	2 [2.3]	85.5 [97.7]	8.5	2.5	0.2
Paper 300	21.2	6.9 [32.4]	14.3 [67.6]	26.9	1.0	0.3
Paper 400	20.0	8.9 [44.7]	11.1 [55.3]	24.3	0.9	0.3
Paper 500	19.2	9.3 [48.3]	9.9 [51.7]	22.7	0.5	0.2
Paper 600	19.2	4 [21]	15.2 [79]	21.2	0.4	0.1
Pine 300	67.2	0 [0]	67.2 [100]	31.5	4.9	0.1
Pine 350	70.7	0 [0]	70.7 [100]	25.2	4.4	0.1
Pine 400	76.3	0 [0]	76.3 [100]	20.8	3.7	0.1
Pine 450	80.5	0 [0]	80.5 [100]	14.8	3.1	0.1
Pine 500	83.4	1.6 [2]	81.8 [98]	12.6	2.9	0.1
Pine 550	86.8	0 [0]	86.8 [100]	11.2	2.7	0.1
Pine 600	91.1	0 [0]	91.1 [100]	9.5	2.3	0.1
Poultry Manure 300	31.9	7.8 [24.5]	24.1 [75.5]	16.9	2.2	2.3
Poultry Manure 350	30.6	11.9 [38.8]	18.7 [61.2]	14.8	1.4	2.0
Poultry Manure 400	32.1	20.2 [63]	11.9 [37]	14.3	0.7	1.2
Poultry Manure 450	35.4	24.2 [68.3]	11.2 [31.7]	9.3	0.5	1.2
Poultry Manure 500	27.8	11.1 [39.8]	16.8 [60.2]	17.9	0.5	1.1
Poultry Manure 550	28.1	14 [49.9]	14.1 [50.1]	15.6	0.3	1.1
Poultry Manure 600	28.7	12.2 [42.7]	16.4 [57.3]	14.3	0.4	0.9
Raw Dairy Manure	51.2	-	-	-	-	2.1
Mixture 220	22.9	-	-	-	-	2.1

Mixture 240	17.7	-	-	-	-	2.0
Switchgrass 2	-	-	-	-	-	-
Pine 2	31.9	7.8 [24.5]	24.1 [75.5]	16.9	2.2	2.3
Mixed Hardwood	-	-	-	-	-	-
Mixed Woodchips	85.9	-	-	-	-	0.4
Leaves	60.7	-	-	-	-	1.1
Grass Clippings	53.5	-	-	-	-	4.9
Brush	84.0	-	-	-	-	0.1
Bull Manure feedstock	43.8	0.6 [1.4]	43.2 [98.6]	44.5	5.8	0.6
Corn feedstock	43.4	0 [0]	43.4 [100]	42.3	5.6	0.5
Dairy Manure feedstock	44.5	0 [0]	44.5 [100]	44.5	5.9	0.9
Hazelnut feedstock	48.7	0 [0]	48.7 [100]	45.5	5.6	0.2
Oak feedstock	47.1	1.6 [3.4]	45.5 [96.6]	45.0	5.8	0.1
Pine feedstock	47.0	0 [0]	47 [100]	47.1	5.7	0.0
Poultry Manure feedstock	25.3	0 [0]	25.3 [100]	47.1	3.1	2.1

[a]Values refer to pyrolysis temperature; where no temperature is indicated, information is included in Supplementary Table S1
[b]data not available

Supplementary Table S4. Total elemental analysis of biochars and feedstocks.

HHT[a] (°C)	P	K	S	Ca	Mg (mg/kg)	Na	Fe	Mn	Zn	Si
					Bull Manure					
60	1142	9533	570	3883	1836	1806	67	23	66	40
300	3014	20017	1102	9412	3952	2712	376	137	162	213
350	2644	24389	857	10518	4277	3062	322	150	133	125
400	3119	28939	859	10088	4841	3089	256	141	165	239
450	2508	30405	917	8450	4314	2927	176	121	138	97
500	3115	33477	928	9432	4925	3518	267	146	167	613
550	3064	32808	1019	11109	5218	3156	417	178	320	416
600	2952	35820	1023	9386	5071	2937	311	165	193	146
					Corn					
60	526	7987	433	4929	3565	468	257	56	59	144
300	1369	17052	697	6480	5883	492	963	142	132	90
350	1889	21486	731	6136	6307	854	558	129	66	205
400	1812	20234	712	7254	6583	904	897	160	49	364
450	2148	25707	790	7317	8031	1112	815	176	64	253
500	1852	24817	739	11699	9510	1384	1063	199	72	241
550	2093	23929	731	9804	8891	778	845	208	82	335
600	2114	24616	801	9383	8582	1539	1362	226	70	322
					Dairy Manure					
60	762	3861	1045	5437	1801	1618	99	15	56	83
300	1152	8986	1799	11094	3934	3270	208	52	90	115

350	1810	10074	1601	10859	4278	3698	317	56	98	154
400	1466	10345	1484	12808	4258	3569	305	53	87	112
450	2001	11756	1608	13473	5068	4009	349	78	121	190
500	1754	9630	1438	12569	4610	2223	396	79	80	nd
550	2358	13388	1793	25702	6357	4424	754	113	142	350
600	2433	13236	1630	13997	5366	4538	398	98	114	310
Hazelnut										
60	88	1619	73	1255	230	388	30	5	5	nd
300	397	5166	263	3726	790	471	92	20	14	7
350	279	4142	136	2580	496	311	57	30	13	nd
400	298	4285	162	2821	554	488	29	13	10	5
450	277	4748	568	2598	490	244	35	26	5	nd
500	275	4297	152	2693	494	447	28	15	13	11
550	348	5121	128	2823	563	386	51	29	12	nd
600	329	5162	173	3262	587	407	42	21	20	13
Oak										
60	nd	251	10	587	63	222	40	7	47	nd
300	6	725	78	752	46	297	5	12	5	5
350	11	1147	182	1097	41	339	1453	23	109	nd
400	5	1462	86	1061	61	321	169	15	33	4
450	43	1664	74	1023	25	229	162	24	23	nd
500	5	1171	100	1538	57	330	16	22	11	11
550	29	1274	100	1609	41	277	323	27	15	nd
600	nd	2061	137	1210	100	52	158	23	23	nd

					Pine					
60	nd	196	308	1480	143	119	126	28	46	nd
300	255	692	114	2927	680	327	149	142	23	22
350	49	387	48	1940	389	134	40	131	21	nd
400	35	373	103	2247	482	351	1166	258	66	10
450	nd	996	1692	2194	667	93	418	297	45	nd
500	1	682	81	2741	796	332	69	259	44	nd
550	nd	734	237	2255	707	232	110	298	38	nd
600	14	775	231	2167	604	320	820	349	60	nd
					Poultry Manure					
60	16684	24053	3426	153209	6063	3778	972	282	359	52
300	26414	40013	4714	157531	8914	3868	1779	450	515	120
350	21256	31751	3556	215648	7309	4218	1464	426	394	nd
400	17957	28109	2983	265729	7164	3209	1276	397	352	nd
450	17329	27400	2898	267804	6388	3695	1069	364	311	nd
500	30555	48616	4593	204205	10436	4537	2034	566	601	nd
550	20147	32126	3231	252608	7277	4048	1513	431	451	nd
600	23596	36775	3429	242788	8769	3457	1522	466	595	nd
					Digested Dairy Manure					
300	5391	14954	2948	20185	8757	3808	1710	128	129	nd
400	6446	16604	2720	22552	9733	4405	1656	145	131	nd
500	5649	14937	1880	18505	8498	3861	2371	162	224	nd
600	8269	20852	2863	26518	11744	5051	2356	191	200	nd

Food										
300	5874	13018	1016	28177	3337	9852	2258	74	49	nd
400	5007	14557	832	51745	5341	9008	4431	179	39	nd
500	7524	21340	1042	53779	4461	13703	2427	118	64	nd
600	8150	27949	1210	73534	6567	14503	5063	201	64	39
Paper										
300	827	2783	312	258128	2428	256	4274	136	26	141
400	830	3279	280	266234	2831	453	4925	148	31	161
500	818	3339	227	289226	2739	295	4794	152	34	145
600	937	3848	321	311232	2940	370	6037	160	51	256
Grass Clippings										
500	11965	61286	6268	20622	6180	2727	1557	360	150	400
Leaves										
500	2072	10840	1034	54550	3616	1682	1504	555	70	341
Brush										
500	132	870	112	7564	441	368	94	142	59	16
Mixed Woodchips										
500	270	1573	193	5427	1267	311	4208	270	93	163
Poultry Manure 2										
300-600	43344	70520	15797	76770	16906	13460	3180	796	1193	952
Composted Dairy Manure										
500	6011	12824	2155	38388	12534	1219	9119	542	172	198
Mixture										
220	13527	7801	1859	44211	3465	4680	10993	236	124	277

240	14397	8037	2030	46554	3581	4787	11664	251	124	272
Corn Stover 3										
515	1769	10101	248	11384	5059	413	5709	320	52	466
Rice Husk										
800	442	6703	171	1637	835	597	29	22	29	831
Carbonized Pine										
700-750	447	5391	189	4702	1445	417	224	366	23	78
Peanut										
480	1986	16266	844	4741	2478	576	1039	137	36	155
Grass Clippings 2										
n/a	507	10794	745	1317	1407	1539	6798	74	19	173
Soybean										
500	564	37789	1127	15651	11715	1527	699	58	28	87
Switchgrass										
500	1161	5354	767	9712	2953	532	516	129	71	245
Switchgrass 2										
500	1255	10801	665	9600	3030	395	10498	100	156	122
Pine 2										
500	607	4772	494	15431	1991	486	28534	478	150	82
Mixed Hardwood										
450-500	121	3671	123	4729	545	481	1141	203	30	85
Mixed Softwood										
450-500	56	1103	65	3749	779	371	114	310	34	71
Mixed Vegetation										

450-500	73	1776	70	2912	255	208	474	74	4	74

[a]HHT highest heating temperature

Supplementary Table S5. Exchangeable bases and soil reaction.

Biochar	pH_{water}	pH_{KCl}	EC	CEC	Ca	Mg	K	Na
			(dS/m)	(mmol$_c$/kg)				
Soybean	-	-	3.8	-	-	-	-	-
Switchgrass	-	-	0.5	-	-	-	-	-
Bull Manure 300[a]	-	8.2	-	335.5	149.9	97.2	264.3	42.0
Bull Manure 350	-	9.3	-	-	-	-	-	-
Bull Manure 400	-	9.8	-	367.3	214.5	122.8	377.3	46.9
Bull Manure 450	-	9.6	-	-	-	-	-	-
Bull Manure 500	-	9.5	-	264.4	208.5	114.0	590.2	59.8
Bull Manure 550	-	9.5	-	-	-	-	-	-
Bull Manure 600	-	9.5	-	335.5	88.3	67.7	464.1	54.4
Rice Husk	-	-	0.3	-	-	-	-	-
Carbonized Pine	-	-	0.5	-	-	-	-	-
Composted Dairy Manure	10.3	9.7	0.8	-	-	-	-	-
Composted Dairy Manure + Wood	9.8	9.7	0.5	-	-	-	-	-
Corn 300	7.3	8.2	1.7	752.8	279.8	250.7	353.6	5.8
Corn 350	-	9.4	-	-	-	-	-	-
Corn 400	9.2	9.7	1.7	796.2	192.2	189.9	452.2	3.5
Corn 450	-	9.4	-	-	-	-	-	-
Corn 500	9.9	9.3	1.9	516.6	197.2	132.5	402.3	5.4

Corn 550	-	9.4	-	-	-	-	-	-
Corn 600	10.0	9.4	2.0	385.4	163.2	106.6	391.6	0.9
Dairy Manure 300	-	8.6	-	286.4	66.6	27.2	42.9	25.7
Dairy Manure 350	-	9.1	-	-	-	-	-	-
Dairy Manure 400	-	9.6	-	175.3	136.7	41.2	78.1	38.7
Dairy Manure 450	-	9.5	-	-	-	-	-	-
Dairy Manure 500	-	9.6	0.6	112.1	135.1	29.1	57.6	42.7
Dairy Manure 550	-	9.7	-	-	-	-	-	-
Dairy Manure 600	-	9.7	-	96.8	90.2	15.6	60.5	62.8
Digested Dairy Manure 300	9.0	8.3	0.6	-	-	-	-	-
Digested Dairy Manure 350	9.2	8.3	1.8	-	-	-	-	-
Digested Dairy Manure 400	9.3	8.6	0.6	-	-	-	-	-
Digested Dairy Manure 450	10.2	9.3	1.9	-	-	-	-	-
Digested Dairy Manure 500	9.7	8.9	0.6	-	-	-	-	-
Digested Dairy Manure 550	10.0	9.2	1.9	-	-	-	-	-
Digested Dairy Manure 600	10.0	9.4	0.7	-	-	-	-	-

Mixed Softwood	-	-	0.1	-	-	-	-	-
Peanut	-	-	0.5	-	-	-	-	-
Food 300	7.6	7.5	1.8	-	-	-	-	-
Food 400	8.6	8.1	1.8	-	-	-	-	-
Food 500	9.7	9.5	1.8	-	-	-	-	-
Food 600	10.8	10.9	2.5	-	-	-	-	-
Poultry 2	-	-	7.5	-	-	-	-	-
Hazelnut 300	6.3	6.8	1.5	58.9	9.9	-1.2	5.5	-2.1
Hazelnut 350	-	7.6	-	-	-	-	-	-
Hazelnut 400	7.7	8.7	1.4	102.5	11.2	1.2	17.9	0.7
Hazelnut 450	-	8.7	-	-	-	-	-	-
Hazelnut 500	8.6	8.6	1.5	117.9	21.0	3.6	41.1	3.0
Hazelnut 550	-	8.3	-	-	-	-	-	-
Hazelnut 600	8.8	8.2	1.6	56.3	11.9	1.7	26.8	-0.3
Corn 3	-	-	1.0	-	-	-	-	-
Grass Clippings 2	-	-	0.9	-	-	-	-	-
Mixed Vegetation	-	-	0.1	-	-	-	-	-
Kuikui	-	-	-	-	-	-	-	-
Macadamia	-	-	-	-	-	-	-	-
Corn 2	-	-	1.5	-	-	-	-	-
Oak 300	4.2	4.5	3.1	413.7	32.8	2.3	22.2	2.1
Oak 350	-	5.2	-	-	-	-	-	-
Oak 400	4.6	6.2	2.8	260.5	22.3	1.4	14.8	1.1

Oak 450	-	7.5	-	-	-	-	-	-
Oak 500	5.8	8.0	3.8	147.2	2.9	-0.8	7.4	-0.1
Oak 550	-	8.0	-	-	-	-	-	-
Oak 600	6.4	7.9	4.3	125.8	0.1	1.4	7.4	0.5
Paper 300	7.8	8.2	0.3	-	-	-	-	-
Paper 400	8.3	8.4	0.2	-	-	-	-	-
Paper 500	9.4	9.5	0.1	-	-	-	-	-
Paper 600	11.5	11.6	0.2	-	-	-	-	-
Pine 300	6.7	7.4	0.3	288.5	52.6	4.5	5.9	1.0
Pine 350	-	5.3	-	-	-	-	-	-
Pine 400	4.6	7.2	0.1	303.6	-2.6	-0.1	3.0	0.0
Pine 450	-	7.4	-	-	-	-	-	-
Pine 500	5.6	6.9	0.1	239.7	4.9	1.7	10.3	0.6
Pine 550	-	5.2	-	-	-	-	-	-
Pine 600	6.0	7.0	0.1	153.8	9.4	3.0	6.2	0.2
Poultry Manure 300	8.1	8.9	4.3	362.4	1108.1	282.7	583.6	86.8
Poultry Manure 350	-	9.7	-	-	-	-	-	-
Poultry Manure 400	9.8	9.8	3.0	165.5	1211.0	155.4	376.0	57.8
Poultry Manure 450	-	9.7	-	-	-	-	-	-
Poultry Manure 500	10.6	10.0	3.8	77.8	1094.7	131.7	326.0	51.4
Poultry Manure 550	-	10.0	-	-	-	-	-	-

Poultry Manure 600	10.7	10.3	3.7	180.4	1098.3	126.1	464.5	71.8
Dairy Manure	10.7	10.3	6.0	-	-	-	-	-
Mixture 220	-	-	1.0	-	-	-	-	-
Mixture 240	-	-	0.8	-	-	-	-	-
Switchgrass 2	-	-	0.5	-	-	-	-	-
Pine 2	8.1	8.9	4.3	362.4	1108.1	282.7	583.6	86.8
Mixed Hardwood	-	-	0.2	-	-	-	-	-
Mixed Woodchips	7.9	8.0	0.9	-	-	-	-	-
Leaves	9.0	8.6	0.6	-	-	-	-	-
Grass Clippings	9.6	9.2	6.7	-	-	-	-	-
Brush	8.4	8.6	0.1	-	-	-	-	-
Bull Manure feedstock	-	-	-	-	-	-	-	-
Corn feedstock	-	-	-	-	-	-	-	-
Dairy Manure feedstock	-	-	-	-	-	-	-	-
Hazelnut feedstock	-	-	-	-	-	-	-	-
Oak feedstock	-	-	-	-	-	-	-	-
Pine feedstock	-	-	-	-	-	-	-	-
Poultry Manure feedstock	-	-	-	-	-	-	-	-

[a]Values refer to pyrolysis temperature; where no temperature is indicated, information is included in Supplementary Table S1

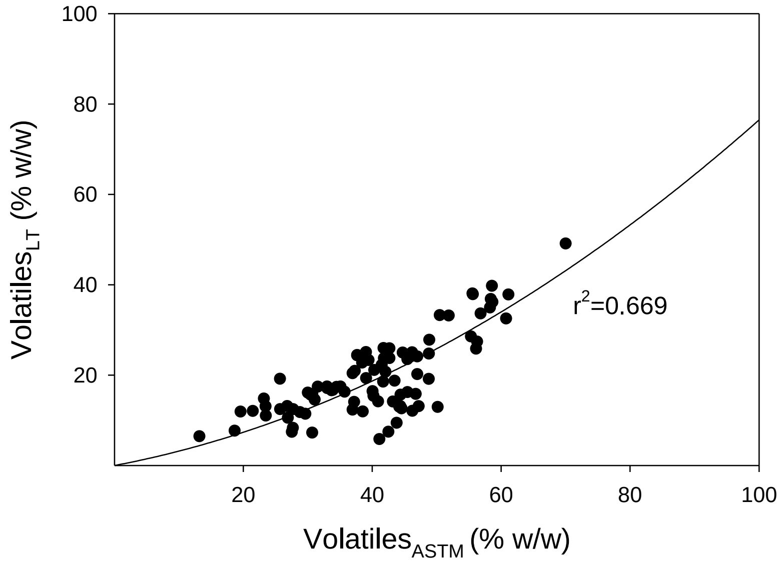
Supplementary Table S6. Decomposition temperature of biomass components.

Biomass Component	Heating Rate (˚C/min)	Pyrolytic Decomposition Temperature (˚C)	Reference
Hemicellulose	6-60	197-257	Demirbas and Arin (2002)
Hemicellulose (Xylan)	50	190-227	Raveendran et al. (1996)
Hemicellulose (from pine)	10	200-300	Wang et al. (2009)
Cellulose	6-60	237-347	Demirbas and Arin (2002)
Cellulose (Whatman filter paper)	50	300-440	Raveendran et al. (1996)
Cellulose (from wood)	50	300-424	Raveendran et al. (1996)
Cellulose (from pine)	10	300-450	Wang et al. (2009)
Lignin	6-60	277-497	Demirbas and Arin (2002)
Lignin	50	250-550	Raveendran et al. (1996)
Lignin	n/a	200-500	Browne (1958)
Lignin (alkali treated)	50	140-500	Raveendran et al. (1996)
Lignin (acid treated)	50	200-427	Raveendran et al. (1996)

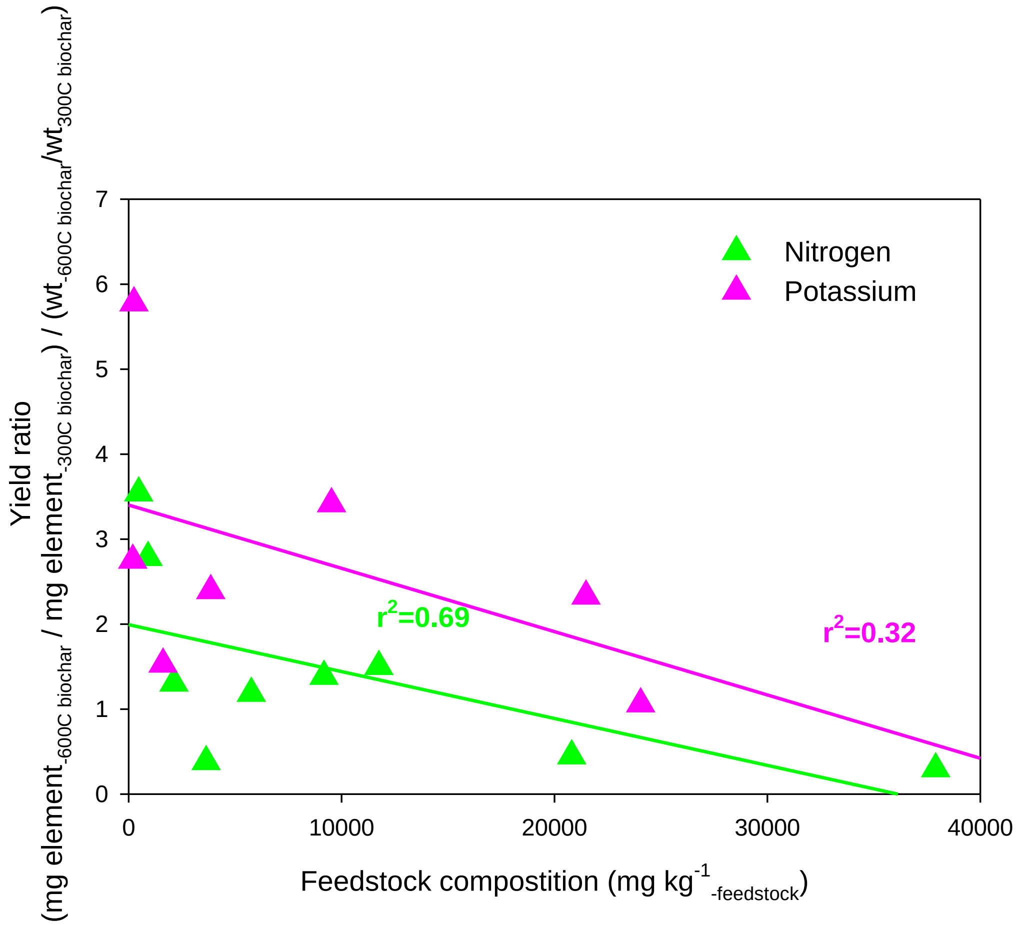
Supplementary Table S7. Losses of inorganic species during pyrolysis.

Element (form)	Feedstock	Heating Rate (˚C/min)	Treatment Temperature (˚C)	Proportion Devolatilized (% w/w)	Reference
N (total)	woody & herbaceous biomass	rapid	<400	>50	Lang et al. (2005)
N (total)	corn stover; cow, chicken & pig manure	gradual, 1 h soak	400[a]	>81	Huang et al. (2011)
S (total)	woody & herbaceous biomass	rapid	<500	>50	Lang et al. (2005)
S (organic)	straw	rapid	<400	35-50%	Knudsen et al. (2004)
S (inorganic)	straw	rapid	<500-600	insignificant amounts	Knudsen et al. (2004)
K (chloride)	pure compounds	10	400-850	2.6	Arvelakis et al. (2004)
K (chloride)	pure compounds	10	850-1150	96.4	Arvelakis et al. (2004)
K (carbonate)	pure compounds	10	400-850	0.6	Arvelakis et al. (2004)
K (sulfate)	pure compounds	10	400-850	0.8	Arvelakis et al. (2004)
K, Na, Ca, Mg (organic)	straw	1.4-248	180-500	nearly all	Olsson et al. (1997)
K, Na, Ca, Mg (inorganic)	straw	1.4-248	180-500	insignificant amounts	Olsson et al. (1997)
K, Na, Ca, Mg (inorganic)	straw	1.4-248	>500	increase with temperature	Olsson et al. (1997)
Ca (carbonate)	pure compounds	10	600-850	44.3	Arvelakis et al. (2004)

[a] combustion



Supplementary Fig. S1. Relationship between volatile contents determined by ASTM and the modified LT method (see text for description of methods; n=2).



Supplementary Fig. S2. Relationship between N and K concentration in feedstock and the enrichment of N and K in biochar produced at 600 °C compared to 300 °C.

Supplementary Fig. S3. Relationship between proximate analyses and (a) cation exchange capacity (CEC) (Rajkovich et al. 2011); (b) growth of fully fertilized maize from a greenhouse experiment using 2% (w/w) biochar application to an Alfisol from Upstate New York (U.S.) with neutral pH (Rajkovich et al. 2011); (c) root:shoot ratio of the same greenhouse experiment (Rajkovich et al. 2011); (d) H:Corg ratios; and (e) O:Corg ratios.

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