BIOCHAR AS A CARBON SEQUESTRATION MECHANISM: DECOMPOSITION, MODELLING, AND POLICY

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by
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ABSTRACT

Black carbon, or biochar (BC), has a strong but complex potential as a tool for climate change mitigation, due to its high carbon (C) stability, through its application within specific biomass management systems, and depending on the policy tools necessary to establish it effectively within climate change mitigation projects. The term “black carbon” encompasses a spectrum of materials produced during incomplete combustion, including soot and charcoal, while “biochar” is used to distinguish the material from charcoal created for fuel, and to denote its particular application in C sequestration and emission-reducing projects as a soil amendment.

Understanding the influence of production temperature, feedstock, and other initial properties on BC stability is critical for evaluating or managing terrestrial C stocks. This thesis quantifies C loss in BCs produced at 7 different temperatures from 6 different feedstocks as well as the original materials through a 3-year microbial incubation in sand matrices. Carbon losses are interpreted using a number of properties, including Fourier-transformed infra-red spectra. High temperature BCs were characterized by lower volatile and higher fixed C contents and the increasing dominance of aromatic C compounds in increasingly condensed forms. 300°C BCs lost 17.8% more C than 600°C BCs, which did not show significant C losses. It was found that production temperature has a greater influence on 3-year C stability than feedstock, likely due to the different temperature ranges at which different organic compounds are modified by heating. However, the C debt or credit ratio, which takes into account the C losses from the original feedstock that are incurred upon charring, is highly sensitive to feedstock type. Corn BCs attained ratios of 2.29-2.81, while no oak or pine chars reached the “break-even ratio” of 1 after 3 years.

The introduction of cook stoves that produce BC as well as heat for cooking into small farm households in western Kenya is an example of a specific system in which BC production could be applied. System dynamics modelling was used to: (i) investigate the climate change impact of prototype and refined BC-producing pyrolytic cook stoves and improved combustion cook stoves in comparison to conventional cook stoves; (ii) assess the relative sensitivity of the stoves to key parameters; (iii) quantify the effects of different climate change impact accounting decisions. Simulated reductions in greenhouse gas (GHG) impact from a traditional 3-stone cook stove baseline range between 2.56-4.63 tCO$_2$e/household/year for an improved combustion stove and 2.58-5.80 tCO$_2$e/household/year for the pyrolytic stoves, of which BC directly accounts for 14-50%. The magnitude of these reductions is about twice as sensitive to baseline wood fuel use and the fraction of non-renewable biomass (fNRB) of off-farm wood that is used as fuel as to farm age/soil degradation status or stability of biochar. Reductions in GHG impact decrease if a household must access non-renewable fuel sources. Stoves with higher wood demand are less sensitive to changes in baseline fuel use and rely on biochar for a greater proportion of their reductions.

This thesis investigates policy and methodology aspects of BC systems used for carbon management, including the criteria for establishing additionality, baselines, permanence, leakage, system drivers, measurement, verification, economics, and development for successful stand-alone projects and carbon offsets. Findings include that applying baselines of biomass decomposition rather than total soil carbon is effective and supports a longer crediting period than is currently standard. Explicitly designing a BC system around “true wastes” as feedstocks combined with safe system drivers could minimize unwanted land-use impacts and leakage With biochar production introduced into bioenergy systems, under a renewable biomass scenario,

the change in emissions increases with higher fuel use, rather than decreasing. Integrating these findings with system-specific analysis and an increased understanding of C stability in BCs should inform the design of effective applied BC systems.

BIOGRAPHICAL SKETCH

Thea Leslie Whitman grew up in White Rock, Nova Scotia, Canada with her mother and father, brother, and two sisters. She attended Gaspereau Elementary School, Wolfville Junior High, and Horton High School. She earned a B.Sc. in Environmental Biology at Queen's University in Kingston, Ontario, where she spent one year abroad studying at Leeds University in the U.K. and earned the subject medal in Environmental Studies. She began her M.S. studies at Cornell in 2008.

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CHAPTER 1

BLACK CARBON DECOMPOSITION ACROSS PRODUCTION TEMPERATURES AS RELATED TO ITS INITIAL PROPERTIES[1]

Abstract

Understanding the influence of production temperature, feedstock, and other initial properties on black carbon (BC) stability is critical for evaluating or managing terrestrial carbon stocks. This study quantified carbon (C) loss in BCs produced at 7 different temperatures from 6 different feedstocks as well as the original materials through a 3-year microbial incubation in sand matrices. All materials were analysed using Fourier-transformed infra-red (FTIR) spectroscopy, proximate analysis (measuring volatile matter, ash content, and fixed C) and selected materials were analysed using ^{13}C-benzene nuclear magnetic resonance (NMR). Carbon losses were then interpreted in the context of these parameters, production temperature, and feedstock. High temperature BCs were characterized by lower volatile and higher fixed C contents and the increasing dominance of aromatic C compounds in increasingly condensed forms. 300°C BCs lost 17.8% more C than 600°C BCs, which did not show significant C losses. It was found that production temperature has a greater influence on 3-year C stability than feedstock, likely due to the different temperature ranges at which different organic compounds are modified by heating. However, the C debt or credit ratio, which takes into account the C losses from the original feedstock that are incurred upon charring, is highly sensitive to feedstock type. Corn BCs attained ratios of 2.29-2.81, while all oak and pine chars remained

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below the “break-even ratio” of 1 after 3 years. These findings are instructive for those who are interested in biomass C management for climate change mitigation or better understanding terrestrial BC cycling.

1.1 Introduction: Black carbon and the environment

The term “black carbon” (BC) encompasses a spectrum of materials produced during incomplete combustion, which range from partially charred organic matter to charcoal, soot, and graphite [1-3]. It is formed primarily through two processes: as a solid residue of combustion (“charcoal”) or through the condensation of volatiles formed in flames (“soot”) [1]. While soot and charcoal share many properties, such as high aromaticity and hydrogen-poor structures, their different origins also give them important differences in chemical and physical characteristics such as size, transportability, and reactivity [2]. In this study, we consider more charcoal-like compounds, but we will refer to these as black carbons (BCs).

Our understanding of BC in the global carbon cycle is growing, but many questions remain [2]. The fraction that black carbon makes up of soil organic carbon (SOC) is highly variable across systems, constituting up to 82% of all SOC in some soils, but having a minimal presence in others [2, 4]. While some of this variation is certainly due to differences in measurement method used and the operational definition of BC, it is clear that BC is an important component of the global carbon cycle, particularly because it degrades relatively slowly. The age of charcoal found in natural soils has been found to be comparable to or older than the oldest fractions of SOC [5, 6]. While it can be degraded both chemically and biologically, this occurs at rates much slower than for fresh organic matter [7, 8]. The high stability of BC has resulted in recent interest in its potential for mitigating climate change by acting as a highly stable pool of stored carbon [9-12].

As interest grows in manipulating the global carbon cycle to promote greater non-atmospheric storage by increasing SOC pools or by producing BC (often referred to in this context as biochar) it becomes important that we be able to better understand and, ultimately, predict the stability of BC [12]. Because materials designated simply as “black carbon” or “biochar” include diverse materials that differ substantially from one another, we aim to progress toward a quantitative understanding of what properties control BC decomposition. Important factors known to impact stability include the feedstock, temperature, and charring time used during BC production as well as the environmental conditions to which the BC is subjected [13-15]. Chemical or physical changes correlated with increasing production temperatures include the relative decrease in aliphatic C structures and concomitant relative increase of aromatic C structures, decreasing H/C and O/C ratios as dehydration reactions take place, decreasing volatile mass content, and increasing pore space as BCs are produced at increasing temperatures [7, 13, 16]. However, quantifying these trends using BC incubations has been difficult. Plotting linear correlations between % C loss and declining H/C and O/C ratios (due to dehydration reactions), O-alkyl groups, and aryl groups for temperatures below 350°C yield relatively strong correlation coefficients of 0.70-0.90 [13], but for materials heated to 250°C-650°C, linear correlations between measured total C mineralization and surface area, volatile weight content, all yield correlation coefficients ≤ 0.35 [7].

Based on apparent discontinuities in physical and chemical properties of BC produced along a temperature gradient, Keiluweit *et al.* [16] have recently developed a scheme dividing the continuum of charred organic matter (100°C-700°C) into five general phases: unaltered plant material, transition char, amorphous char, composite char, and turbostatic char. They suggest that this approach may help explain the “paradox of refractory-labile black carbon” [17].

In this three-year study, we attempt to further our understanding of how changes in organic matter as it is charred at increasing temperatures are related to its potential decomposition. We hypothesized that (i) lower BC decomposition would be generally correlated with increasing aromaticization of organic matter, decreasing volatile carbon content, and increasing charring temperature and (ii) discontinuities in decomposition and its correlated properties may occur at different temperatures for each biomass type, and allow for broad categorization of different BCs.

1.2 Materials and methods

1.2.1 Black C preparation

BC materials were produced from seven different feedstocks: corn stover (*Zea mays* L.), oak shavings (*Quercus spp.*), pine shavings (*Pinus spp.*), fryer/broiler poultry bedding consisting primarily of manure (*Gallus gallus domesticus*) mixed with sawdust, bull bedding consisting of manure (*Bos primigenius taurus*) mixed with sawdust, dairy bedding consisting of manure (*Bos primigenius taurus*) mixed with rice hulls (*Oryza sativa*), and hazelnut shells (*Corylus spp.*). Each feedstock was used to produce BC at 7 different temperatures (300, 350, 400, 450, 500, 550, and 600°C), using slow pyrolysis (DaisyReactor, BestEnergies, Inc., Cashton, WI, USA). Approximately 3 kg pre-dried (~10% moisture) feedstock were placed in the main chamber, which was thoroughly purged with N_2 (with the mixer running). Over 80-90 minutes, the material was heated to the target temperature at a rate of a few °C/minute and isothermically charred at the final temperature for at least 15 minutes before turning off the furnace and allowing the main chamber to cool. The material was collected under N_2 to reduce rapid oxidation and auto-ignition. The materials were stored in plastic bag-lined galvanized epoxy-lined tin paint cans from which the ambient air was purged with a vacuum pump and replaced with argon gas. As well, samples of the original feedstock materials were dried at 60°C.

1.2.2 Sample preparation

Each BC was weighed into an 8x5 mm tin capsule (Elemental Microanalysis) and analysed for initial C content in a PDZ Europa ANCA-GSL CN analyzer (PDZ Europa Ltd., Sandbach, UK). Bottles (30mL) were acid-washed (10% HCl) and filled with 19.2g white quartz sand (Sigma Aldrich no. 274739, 50+70 mesh; heated at 500°C in a muffle furnace for 24h). Each BC was slightly crushed with a mortar and pestle and sieved to a particle size of 500-2000µm. 0.8g of sieved BC were hand-mixed into each sand-filled bottle. Four blank replicates of only sand were also prepared.

Water-holding capacity (WHC) was determined for a sample of each BC-sand mixture by gravimetric method using funnels and filter paper, where mass difference after saturating the mixture with distilled water, allowing it to completely drain, freely. BC-sand mixtures were grouped in three categories – low (22-25 mass %), medium (26-29 mass %), and high (30+ mass %) WHC.

A microbial inoculation was prepared by incubating a soil sample from a historical charcoal blast furnace site in Cartersville, GA [18]. The soil was noted for high BC content and microbial activity, so we expected that the microbial community would be adapted to the presence of BC. The sample had been stored at 5°C after sampling, and was incubated under 60% WHC at 30°C for 7 days. A sample of the incubated soil was then mixed with distilled water to a 1:50 w/v soil:water ratio, was shaken gently for 30 minutes, and filtered through a Whatman no. 1 filter paper. The resulting solution had nutrients added to give the following concentrations: 4mM NH_3NO_3, 4mM $CaCl_2$, 2mM KH_2PO_4, 1mM K_2SO_4, 1mM $MgSO_4$, 25µM H_3BO_3, 2µM $MnSO_4$, 2µM $ZnSO_4$, 2µM $FeCl_2$, 0.5µM $CuSO_4$, and 0.5µM Na_2MoO_4. Inoculation and micronutrient solution (1.8mL) were added to each jar, and then sufficient deionized water was added to each jar to bring the jar to 55% WHC.

1.2.3 Incubation and analysis

The bottles were incubated in a temperature-controlled environment at 30°C in aerobic environments – *i.e.*, without caps on and open to the air, with a partial cover to minimize dust deposition and resting in a water bath. They were maintained at 55% WHC by taking the mass of the jars every 3 weeks and adding distilled water to bring them to the appropriate mass. A long-term (3 years - 1,059 days, 3 reps per BC) and a short-term (5 months - 168 days, 4 reps per BC) incubation were prepared, where the bottles were removed after the designated length of time and dried at 105°C. Each sample was poured out into a tray. Half of each sample was reserved and half was poured into ball milling jars and ground to a fine powder. The powdered samples were stored in glass vials. A subsample of each vial was massed in a 12.5 x 5mm tin capsule (Elemental Microanalysis) and analysed for total C in a NC2100 Soil Analyzer (ThermoQuest Italia S.p.A., Milan, Italy).

Total fraction of C lost during incubation was calculated for each BC. As well as considering C loss in relation to the initial C contents of charred materials, because a substantial portion of C is lost during the charring process, we also consider C loss in terms of the total C remaining after decomposition in relation to the original, pre-charred material. This approach is important for those interested in C management for climate change mitigation. The percentage of C remaining in relation to pre-charred material was calculated for each incubated BC. This value was then divided by the C remaining in the incubated original materials, giving a “C debt or credit ratio,” where a number >1 indicates that, even though some C was lost during its production, the BC is so much more stable than the original feedstock that more C remains in the BC, while a number <1 indicates that, even if a BC is more stable than the original feedstock, sufficient C loss occurred during its production that this increased stability has not yet resulted in C savings.

1.2.4 BC characterization

1.2.4.1 Proximate analysis

Volatiles, ash, and fixed C content were determined for all BCs using the ASTM methods [19] and a parallel modified method. This modified method was designed to achieve similar metrics to the ASTM tests, but at lower temperatures, to reduce important thermal alteration of the lowest-temperature BCs. Proximate analysis was not applied to the original materials.

For the modified method, significant modifications are as follows: moisture content is determined under Ar gas to prevent O_2 adsorption, over 18 hours rather than the ASTM's 2 hours. Volatile content is also determined under Ar gas and is measured as proportion mass loss after ramping muffle furnace temperature by 5°C min^{-1} from 105°C to 350°C, then maintaining 350°C conditions for 2 hours. The ASTM volatile content methodology recommends 2 min at 300°C, 3 min at 500°C, and then 6 min at 950°C, achieved by moving the crucibles around the furnace and leaving the door ajar or shut, but was modified to 10 min at 950°C in the muffle furnace after opening the door, which causes significant heat loss and spatially variable internal temperatures. Ash content was measured similarly to the modified volatile content measurement method, but under oxic conditions and with no lids on the crucibles. The ASTM ashing methodology recommends heating BCs at 750°C for 6 hours, but was modified slightly to ramping temperature from 105°C to 750°C at a rate of 5°C min^{-1}, heating at 750°C for 6 hours, then decreasing temperature to 105°C before weighing. All samples were placed in individual desiccators upon removal from the oven to limit adsorption of water before weighing.

1.2.4.2 Total elemental analysis

Labware was washed with laboratory detergent, soaked in 10% hydrochloric acid solution overnight, thoroughly rinsed in deionized water, then dried at 85°C. Tall form factor, 25 x 150 mm borosilicate glass tubes were used as both digestion and ashing vessels (#9825-25, Corning Life Sciences, Corning, NY). Boron contamination from borosilicate glassware has been documented, but was accepted for these analyses in favor of using commonly available labware. Air dried BCs were ground with mortar and pestle and sieved to achieve 149-850 µm particle size range. Samples were weighed to 200.0 mg ± 5.0 mg on weighing paper then transferred to digestion or ashing vessels. Each paper was weighed following transfer to account for sample retained on the paper.

Samples were then placed in a cool muffle furnace (Fisher Isotemp Model 126, Thermo Fisher Scientific, Waltham, MA). A steel test tube rack, previously exposed to ashing conditions, was used to hold the digestion tubes upright. Samples were heated from ambient to 500°C over 2 hours and held at 500°C for 8 hours. The furnace was allowed to cool to 175°C before opening the door slightly. Samples were removed after internal temperature reached 30°C. Following this, 5.0 mL HNO_3 was added to each vessel and processed at 120°C on the digestion block until dryness was reached. Tubes were removed from the block and allowed to cool before addition of 1.0 mL HNO_3 and 4.0 mL H_2O_2. Samples were placed back into a preheated block and processed at 120°C to dryness. After cooling, 1.43 mL HNO_3 was added to each tube then vortexed. Deionized water was added to achieve 5% acid concentration, then digestion tubes were sonicated for 10 min (Model 1200, Branson Ultrasonics Corp., Danbury, CT). Contents were then passed through qualitative cellulose filter paper prior to analysis (#42, Whatman Inc., Piscataway, NJ).

Analysis was carried out using an axially viewed inductively-coupled plasma (ICP) trace analyzer emission spectrometer (model ICAP 61E trace analyzer, Thermo Electron, Waltham, Ma.). The analyzer's transfer optics have been replaced with a short depth of field transfer optics to reduce matrix effects.

1.2.4.3 Fourier-Transformed Infra Red (FTIR) analysis

In order to avoid the confounding effects of dissociation of chemical functional groups during the FTIR scan [18], sieved BCs were pH standardized with pH 7 deionised water for 5 days, decanting and replacing the water twice [14]. BCs were air-dried for 2 days and then dried at 60°C. Dry BCs were then ground using a mortar and pestle, and mixed with KBr powder which had been dried at 105°C at a ratio of 3 mg BC : 1000 mg KBr for all BCs created at temperatures below 500°C and at a ratio of 3 mg BC : 2000 mg KBr for all BCs created at 500°C and above. (This adjustment was needed due to the high absorbance in scans of the dark, dense, high temperature BCs and is not expected to change the outcomes relevant to this paper.) The BC-powder mixture was then re-ground by mortar and pestle to ensure homogeneity and stored in a dessicator. Pellets were created using 150-250 mg of powder in a pellet press at 20-30 ft•lbs of pressure. Two pellets were created for each BC. Using a Mattson Model 5020 FTIR Spectrometer (Madison, WI) at wave numbers from 400-4000 cm^{-1}, each sample was scanned 100 times, with a resolution of 4 cm^{-1}, subtracting a blank value obtained form a pure KBr pellet.

Chemical functional groups were proportionally quantified using FTIR spectra and OMNIC 7.4 (Thermo Fisher Scientific Inc., 1992–2007). Wave numbers were assigned as follows [20-23]: 3,425 cm^{-1} to hydroxyl (O–H) stretching of carboxylic acids, phenols, and alcohols as well as amine and amide (N–H) stretching, 2925-2870 cm^{-1} to aliphatic C-H stretching of CH_3 and CH_2, 1,700 cm^{-1} to carbonyl-C and ketonic-C (C=O) stretching, 1,590 cm^{-1} to aromatic-C (C=C) vibrations and stretching, 1,424 cm^{-1} (and 1,460 cm^{-1}) to C-H deformation in lignin and carbohydrates, 1,374 cm^{-1} to aliphatic deformation of CH_2 or CH_3 groups in cellulose and hemicellulose, 1048 to C-O stretching in cellulose and hemicellulose, and 816 cm^{-1} to aromatic C-H out of plane deformation. Relative proportions of selected chemical species were measured by drawing baselines for each peak position, after baseline correction and spectrum normalization.

Baselines were drawn as follows: 3691-3118 for O-H stretching, 3006-2803 for aliphatic CH stretching, 1667-1745 for C=O stretching, 1509-1666 for C=C vibrations and stretching, 1483-1466 for C-H deformation in lignin and carbohydrates, 1400-1330 for C-H deformation in cellulose/hemicellulose, 1145-910 for C-O stretching in cellulose and hemicellulose, and 895-743 for aromatic C-H deformation.

1.2.4.4 Nuclear Magnetic Resonance (NMR) analysis

Properties of selected BCs were determined using ^{13}C-benzene NMR. This technique is based on the fact that the properties of ^{13}C-benzene are influenced by its sorption to the BC in a methanol solution, where different degrees of BC condensation and, thus, diamagnetic ring currents in the different charcoals, result in different chemical shifts in the ^{13}C-benzene. This technique followed that of Smernik *et al.* [24]. Solid-state C magic angle spinning (MAS) NMR spectra were obtained at a frequency of 50.3 MHz on a Varian Unity 200 spectrometer (Varian, Palo Alto, CA). Samples were spun at 5000 ±100 Hz. Chemical shifts were externally referenced to the methyl resonance of hexamethylbenzene at 17.36 ppm. Cross polarization (CP) and dipolar dephasing (DD) spectra were acquired using a 1-ms contact time and a 1-s recycle delay. Direct polarization (DP) spectra were acquired using a 90-s recycle delay. Spin counting was carried out using the method of Smernik *et al*. [25]. The chemical shift of ^{13}C-benzene (-Δδ), which gives an indication of the degree of condensation, was measured, as were proton NMR relaxation rates ($T_{1\rho}H$), which should decrease as the number of unpaired electrons or free radicals increase [24].

1.3 Results

1.3.1 Black carbon mineralization

In general, C loss decreased with increasing production temperature and poultry manure with sawdust materials had the greatest and fastest C loss. After 5 months, the % C remaining was significantly different from any temperature category of BCs only for the original feedstocks, but several different feedstocks were significantly different from each other (Table 1.S1). However, after 36 months, poultry manure with sawdust was the only feedstock that remained significantly different from the other feedstocks. The 60ºC treatment was still significantly different from all other treatments, and the 300ºC temperature category was significantly different from the 600ºC treatment (Table 1.1). Overall, mean %C retention decreased significantly from 5 months to 36 months for BCs (paired t-test, a=0.05).

The C debt or credit ratios are listed in Table 1.S2 for initial BCs and BCs incubated for 36 months. This ratio increased significantly for all bull, corn, dairy, and poultry BCs, reaching values significantly >1 for all corn BCs and some bull, dairy, and poultry BCs. The ratio continued to increase between 5 and 36 months for all bull, corn, and dairy BCs, most poultry BCs, and some oak and pine BCs.

Table 1.1. Mean percent C retention after three years[1]

	60°C^{A}‡	300°C^{aB}‡	350°C^{bBC}	400°C^{bBC}
Bull^{bB}‡	52.9*‡^{bBC}	90.4^{aA}	103.2^{aA}	100.8^{aA}
Corn^{bAB}‡	17.9*‡^{aD}	80.1*^{bAB}	90.3 *‡^{bA}	92.8^{bA}
Dairy^{bAB}‡	44.0 *‡^{cC}	78.3*‡^{bAB}	92.6^{abA}	101.5^{abA}
Oak^{bB}	74.1*‡^{aAB}	88.1^{aA}	92.7^{aA}	93.2^{aA}
Pine^{bAB}‡	83.2*^{aA}	86.3*^{aA}	97.7^{aA}	93.8^{aA}
Poultry^{aA}	42.6 *^{bCD}	64.2*‡^{abB}	82.3^{aA}	86.9*^{aA}
	450°C^{abBC}‡	500°C^{abBC}	550°C^{abBC}	600°C^{bC}
Bull^{bB}‡	89.1*‡^{aA}	95.9^{aA}	94.5^{aA}	106.2^{aA}
Corn^{bAB}‡	97.7^{bA}	85.7‡^{bA}	91.5^{bA}	98.2^{bAB}
Dairy^{bAB}‡	95.1^{abA}	91.3*‡^{abA}	93.2^{abA}	106.4^{aA}
Oak^{bB}	94.2^{aA}	90.0^{aA}	101.5^{aA}	98.3^{aAB}
Pine^{bAB}‡	90.2*^{aA}	86.2^{aA}	88.7^{aA}	87.7*^{aAB}
Poultry^{aA}	85.4*^{aA}	78.6 *^{aA}	83.8^{aA}	77.5*^{aB}

1. Lowercase letters indicate significant differences within feedstock (pairwise comparisons, Tukey-Kramer HSD, a=0.05), uppercase letters represent significant differences within temperature (pairwise comparisons, Tukey-Kramer HSD, a=0.05), asterisks (*) indicate significant differences from 100% C (one-sided t-test, a=0.05), and ‡ indicates significant losses between 5 months and three years (t-test, $p<0.05$). Overall, significant differences between feedstocks and temperatures are indicated with capital letters when original materials are included and with lowercase letters when original materials are excluded (pairwise comparisons, Tukey-Kramer HSD, a=0.05).

1.3.2 Black carbon characteristics

Results for C:N, and pH are listed in Table 1.S3 and total elemental analysis results are listed in Table 1.S4. The poultry manures are particularly high in Ca, while the wood BCs are relatively low in P and K. C:N ratios were very high (300-850) for the wood BCs, mid-range (30-80) for the bull manure with sawdust, dairy manure with rice hulls, and corn stover, and low for the poultry BCs (10-22). Bull manure with sawdust, dairy manure with rice hulls, poultry manure with sawdust, and corn stalks had pHs ranging from around 8-10, while the two wood BCs had lower pHs ranging from around 4.5-8. The pH of the BCs tended to increase with increasing production temperature for most feedstocks.

1.3.3 13-C Benzene NMR analysis

NMR data for selected BCs are listed in Table 1.2. Aromatic condensation

($-\Delta\delta$ value) increases with increasing production temperature, while the NMR-determined % non-aromatic C decreases with increasing production temperature and $T_{1\rho}H$ increases with increasing production temperatures, beyond a point around 400-500°C.

Table 1.2. NMR parameters for selected BCs

Sample	**% Non-aromatic C**		**C_{obs} (%)**		**$-\Delta\delta$ (ppm)**		**$T_{1\rho}H$ (ms)**
	CP	DP	CP	DP	CP	DP	
Bull 400	14.0	9.9	40	105	0.4	0.2	2.5
Bull 500	6.4	5.0	45	93	0.9	0.9	2.8
Bull 600	4.3	5.4	30	70	1.5	1.1	8.3
Corn 400	18.2	14.0	51	110	0.7	0.9	2.9
Corn 500	7.4	3.4	41	86	1.4	1.1	4.0
Corn 600		5.7	33	88	2.8	3.0	5.5
Dairy 400	14.3	10.1	38	86	0.7	0.6	2.1
Dairy 600	4.6	0.8	48	83	2.1	1.9	4.9
Oak 350	14.6	12.8	42	82	0.5	0.6	3.1
Oak 450	7.3	7.5	43	91	1.3	1.2	3.2
Pine 450	10.8	7.3	38	83	1.3	0.9	2.1
Pine 550	5.5	4.9	56	98	2.2	1.6	4.3

1.3.4 Proximate analysis

Volatile C, fixed C, and ash contents measured using the two different methods described are listed in Table 1.3. For most BCs, volatiles are highest at the two lowest temperatures under both measurement techniques, but the mass fraction measured in this category is higher for the ASTM methodology. The exception to this general trend is the poultry manure, which shows little trend in the volatile fraction with increasing charring temperature. Ash contents exhibit a less striking trend, increasing only slightly at higher temperatures. Again, poultry manure with sawdust is the exception, with very high ash contents (~50% by mass for ASTM, ~85% by mass for the modified method). The volatile content as a percentage of ash-free mass was also calculated (not shown), to account for potential confounding effects of high-ash BCs.

1.3.5 Functional chemistry of BCs

With the exception of poultry manure with sawdust, the relative proportions of functional groups as measured by FTIR for a given production temperature across feedstock types are relatively similar (Table 1.4; Figures 1.S1-1.S5; dendrogram showing hierarchical clustering of FTIR spectra in Figure 1.S6). Moving from uncharred biomass to charred biomass, and as charring temperature increases, the proportions of 1,600 cm^{-1} C=C and 816 cm^{-1} aromatic C-H groups increase, while the proportions of 1,700 cm^{-1} C=O, 2925-2870 cm^{-1} CH_2 and CH_3, 3.400 cm^{-1} O-H, 1,375 cm^{-1} CH_2 and CH_3, 1,425 cm^{-1} lignin and carbohydrate C-H, and 1,048 cm^{-1} cellulose and hemicellulose C-O groups decrease. (Spectra from pine are shown as an example in Figure 1.1 and all other spectra are shown in the supporting information [SI].) The FTIR scans of the poultry manure mixed with sawdust (italicized in Table 1.4) were dominated by a strong signal of $CaCO_3$, which obscured peaks of interest, particularly in the fingerprint region.

1.3.6 Correlation of chemical properties and mineralization

Many of the chemical parameters measured correlate relatively well with each other (Tables 1.S5.1 and 1.S5.2). The fraction of C remaining in BCs after 3 years was relatively well correlated with proximate analysis data. However, this significance was highly influenced by a combination of the original materials and the high-volatile-content poultry BCs, without which the R^2 values are insignificant (Table 1.5). Many FTIR peaks were relatively well correlated with the % C remaining. The correlations were performed including and excluding poultry BCs, which were somewhat problematic to analyse due to a strong $CaCO_3$ signal in the FTIR poultry data, and including and excluding 60ºC feedstocks, which also provided much of the strength of correlation.

Table 1.3. Mean values for proximate analysis

Feedstock	Temp (°C)	Volatiles (QT / ASTM)		Ash (QT / ASTM)		Fixed C (QT / ASTM)	
Bull	**60**	73.80%	84.44%	4.66%	5.34%	21.54%	10.21%
	300	38.05%	55.55%	13.42%	7.67%	48.53%	36.78%
	350	36.16%	58.66%	16.26%	8.33%	47.58%	33.02%
	400	20.41%	36.96%	18.92%	9.36%	60.68%	53.68%
	450	25.04%	46.19%	21.68%	9.28%	53.29%	44.52%
	500	15.66%	30.46%	19.87%	10.35%	64.47%	59.19%
	550	25.09%	39.04%	22.88%	10.89%	52.03%	50.06%
	600	16.11%	30.01%	18.25%	10.62%	65.63%	59.37%
Corn	**60**	73.79%	85.21%	8.83%	8.97%	17.37%	5.82%
	300	34.26%	51.69%	15.28%	8.98%	50.46%	39.34%
	350	29.53%	51.71%	19.96%	10.96%	50.52%	37.33%
	400	24.96%	44.73%	24.43%	12.90%	50.61%	42.37%
	450	25.25%	45.63%	24.57%	11.83%	50.18%	42.54%
	500	14.57%	31.08%	31.00%	17.60%	57.33%	56.23%
	550	25.63%	43.01%	28.10%	12.69%	46.27%	44.30%
	600	11.02%	23.49%	38.14%	16.72%	50.84%	59.80%
Dairy	**60**	69.07%	80.87%	4.76%	5.64%	26.17%	13.49%
	300	24.48%	45.36%	12.71%	10.10%	62.81%	44.55%
	350	36.83%	58.39%	30.36%	10.22%	32.81%	31.39%
	400	19.31%	39.06%	15.13%	11.46%	65.57%	49.47%
	450	20.72%	42.06%	30.36%	11.71%	48.93%	46.23%
	500	16.71%	33.90%	18.59%	12.36%	64.69%	53.74%
	550	23.72%	41.82%	38.00%	13.44%	38.29%	44.75%
	600	15.78%	30.72%	14.66%	12.64%	69.56%	56.64%
Oak	**60**	75.61%	88.61%	0.28%	2.00%	24.11%	9.39%
	300	37.81%	61.13%	33.28%	0.35%	28.91%	38.52%
	350	32.52%	60.77%	15.14%	1.09%	52.34%	38.14%
	400	14.17%	40.93%	15.16%	0.78%	70.67%	58.30%
	450	15.64%	44.40%	22.03%	0.59%	62.33%	55.02%
	500	7.26%	30.70%	36.26%	3.72%	56.48%	65.58%
	550	11.93%	38.54%	45.92%	0.58%	42.15%	60.88%
	600	7.41%	27.53%	28.48%	1.31%	64.11%	71.16%
Pine	**60**	77.33%	89.84%	0.76%	1.83%	21.91%	8.32%
	300	28.52%	55.32%	7.12%	1.48%	64.36%	43.20%
	350	27.39%	56.27%	24.37%	0.58%	48.24%	43.15%
	400	16.23%	45.47%	19.90%	1.05%	63.88%	53.48%
	450	19.13%	48.77%	31.43%	1.50%	49.44%	49.73%
	500	12.34%	36.95%	17.27%	1.00%	36.28%	62.25%
	550	15.39%	40.19%	51.38%	0.80%	33.23%	59.01%
	600	8.32%	27.70%	34.57%	1.07%	57.11%	71.22%
Poultry	**60**	34.12%	60.51%	52.08%	36.35%	13.80%	3.14%
	300	15.81%	46.76%	78.98%	46.71%	5.21%	6.54%
	350	13.11%	47.21%	87.97%	51.18%	~0.00%	1.61%
	400	9.43%	43.79%	80.35%	51.74%	10.23%	4.47%
	450	12.09%	46.24%	90.46%	53.60%	~0.00%	0.16%
	500	14.13%	43.22%	78.80%	52.85%	7.07%	3.94%
	550	12.62%	44.56%	84.76%	54.85%	2.62%	0.59%
	600	13.13%	44.35%	82.98%	55.80%	3.89%	~0.00%

Table 1.4. FTIR peak height fraction

	Temp	**3425**	**2925**	**1700**	**1590**	**1460**	**1424**	**1374**	**1048**	**816**
Bull	**60**	0.46	0.13	0.01	0.05	0.07	0.05	0.05	0.17	0.00
	300	0.43	0.13	0.15	0.19	0.04	0.02	0.02	0.01	0.03
	350	0.43	0.09	0.10	0.28	0.01	0.01	0.03	0.00	0.05
	400	0.42	0.05	0.08	0.32	0.01	0.01	0.03	0.01	0.07
	450	0.52	0.02	0.08	0.26	0.01	0.00	0.04	0.04	0.04
	500	0.41	0.05	0.07	0.36	0.01	0.01	0.01	0.01	0.08
	550	0.31	0.05	0.07	0.40	0.00	0.00	0.00	0.01	0.15
	600	0.29	0.05	0.05	0.41	0.00	0.00	0.01	0.00	0.18
Corn	**60**	0.35	0.09	0.00	0.00	0.03	0.02	0.35	0.14	0.00
	300	0.42	0.12	0.13	0.22	0.02	0.01	0.02	0.04	0.02
	350	0.42	0.10	0.10	0.26	0.02	0.00	0.03	0.02	0.05
	400	0.37	0.07	0.06	0.37	0.01	0.00	0.04	0.02	0.06
	450	0.39	0.02	0.04	0.44	0.00	0.00	0.02	0.02	0.07
	500	0.36	0.04	0.04	0.42	0.00	0.01	0.02	0.01	0.11
	550	0.45	0.04	0.04	0.35	0.00	0.00	0.02	0.01	0.09
	600	0.38	0.03	0.05	0.38	0.00	0.01	0.02	0.01	0.13
Dairy	**60**	0.51	0.15	0.00	0.01	0.05	0.04	0.04	0.19	0.00
	300	0.42	0.14	0.20	0.12	0.02	0.02	0.02	0.02	0.04
	350	0.42	0.10	0.12	0.28	0.01	0.01	0.03	0.01	0.02
	400	0.44	0.05	0.07	0.33	0.00	0.02	0.03	0.00	0.06
	450	0.32	0.03	0.07	0.48	0.00	0.01	0.03	0.03	0.04
	500	0.24	0.06	0.06	0.46	0.00	0.00	0.03	0.01	0.15
	550	0.34	0.05	0.05	0.37	0.00	0.00	0.02	0.03	0.14
	600	0.34	0.03	0.02	0.37	0.00	0.00	0.05	0.01	0.18
Oak	**60**	0.49	0.14	0.00	0.01	0.08	0.05	0.05	0.17	0.00
	300	0.47	0.10	0.13	0.14	0.07	0.03	0.02	0.04	0.00
	350	0.49	0.04	0.11	0.27	0.02	0.03	0.03	0.02	0.00
	400	0.48	0.02	0.09	0.30	0.01	0.00	0.03	0.01	0.06
	450	0.33	0.02	0.07	0.38	0.01	0.00	0.02	0.00	0.16
	500	0.41	0.00	0.03	0.38	0.00	0.00	0.02	0.00	0.16
	550	0.02	0.00	0.07	0.52	0.00	0.00	0.00	0.00	0.38
	600	0.19	0.00	0.05	0.42	0.00	0.00	0.00	0.00	0.34
Pine	**60**	0.55	0.13	0.01	0.01	0.05	0.04	0.04	0.18	0.01
	300	0.43	0.10	0.11	0.16	0.04	0.03	0.03	0.08	0.03
	350	0.42	0.08	0.10	0.26	0.03	0.02	0.02	0.01	0.07
	400	0.40	0.08	0.11	0.26	0.03	0.02	0.02	0.01	0.06
	450	0.40	0.02	0.05	0.37	0.00	0.02	0.02	0.00	0.12
	500	0.35	0.03	0.08	0.40	0.00	0.00	0.02	0.00	0.14
	550	0.40	0.03	0.05	0.33	0.00	0.00	0.01	0.00	0.17
	600	0.26	0.05	0.07	0.36	0.00	0.00	0.00	0.00	0.25
Pltry.	**60**	*0.11*	*0.33*	*0.34*	*0.01*	*0.17*	*0.01*	*0.01*	*0.01*	*0.01*
	300	*0.68*	*0.23*	*0.06*	*0.00*	*0.02*	*0.00*	*0.00*	*0.00*	*0.00*
	350	*0.76*	*0.19*	*0.03*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
	400	*0.82*	*0.11*	*0.03*	*0.00*	*0.02*	*0.00*	*0.00*	*0.00*	*0.00*
	450	*0.82*	*0.13*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*
	500	*0.58*	*0.29*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*
	550	*0.75*	*0.14*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*
	600	*0.82*	*0.12*	*0.01*	*0.01*	*0.02*	*0.01*	*0.01*	*0.01*	*0.01*

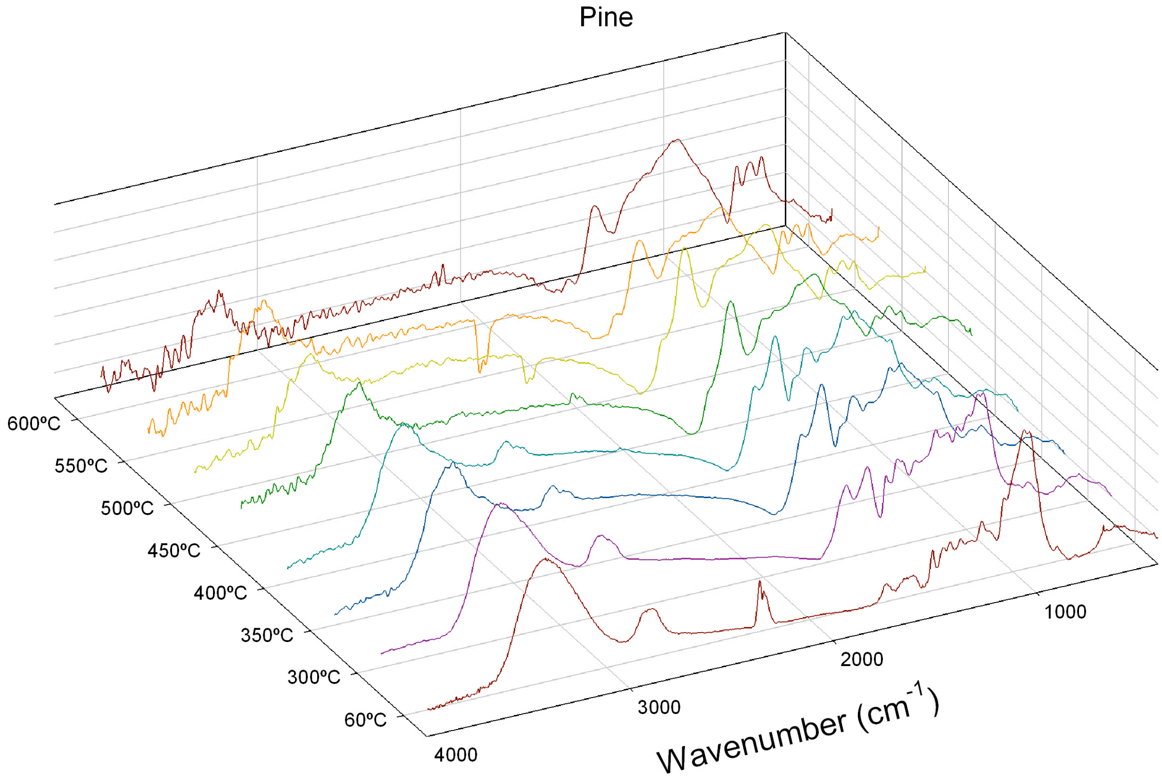


Figure 1.1. Representative set of FTIR spectra for pine feedstock across temperatures

The mean fraction of C remaining after 3 years was correlated with the FTIR peaks at 1590 and 814, using an exponential fit (Figure 1.2). (Because determining FTIR data from poultry was problematic, those data were not included in this analysis.) The fit achieved with the two peaks give similar functions. Because there is less of a gradation in the 814 peaks – peaks at this wavenumber appear in the spectra to any significant degree only after 450ºC or so, by which point there is little C loss – it has a more abrupt curve, producing essentially a straight line at 95 % C remaining.

Table 1.5. Correlation coefficients for mean % C remaining after 3 years and selected parameters. An “ns” indicates no significant slope at the a=0.05 level.

	Sign	All BC data, 5 months	All BC data, 36 months	No 60, 36 months	No Po, 36 months	No Po or 60, 36 months
Volatiles QT	-	ns	0.25	ns	0.52	ns
Volatiles ASTM	-	0.11	0.35	ns	0.47	ns
Ash QT	-	0.29	ns	0.57	0.18	ns
Ash ASTM	-	0.31	0.16	0.58	ns	ns
Fixed C QT	+	0.54	0.48	0.61	0.41	ns
Fixed C ASTM	+	0.46	0.55	0.59	0.46	ns
%Vol/non-ash QT	-	0.43	0.51	0.56	0.51	ns
% Vol/non-ash ASTM	-	0.51	0.57	0.62	0.49	ns
% non-aro C (CP)	-	ns	ns	N/A	N/A	N/A
% non-aro C (DP)	-	ns	ns	N/A	N/A	N/A
-delta (CP)	+	ns	ns	N/A	N/A	N/A
-delta (DP)	+	ns	ns	N/A	N/A	N/A
$T_{1\rho}H$	+	0.25	ns	N/A	N/A	N/A
2925	-	0.39	0.35	ns	0.28	0.17
1700	~0	ns	ns	ns	0.10	0.22
1590	+	0.41	0.45	0.27	0.50	0.21
1460	-	0.35	0.36	ns	0.30	ns
1424	-	0.09	0.19	ns	0.29	ns
1374	-	0.08	0.35	0.11	0.54	ns
1048	-	0.08	0.37	ns	0.57	0.13
816	+	0.07	0.21	0.16	0.18	ns

1.4 Discussion

1.4.1 BC mineralization: the role of temperature and feedstock

The magnitude of net C loss determined in this study is consistent with other black carbon incubation experiments of similar durations using direct [7, 8] and indirect [14] measurements of CO_2 evolution. Although the very slow loss rates associated with BCs are not calculable using this study’s data, it is likely that the rate of C loss by 3 years has slowed to a very low rate, with half lives on the order of hundreds to thousands of years [7, 8]. Thus, we could potentially consider the C loss after 3 years under ideal moisture and temperature conditions to represent the fraction of BC C that is relatively “stable”.

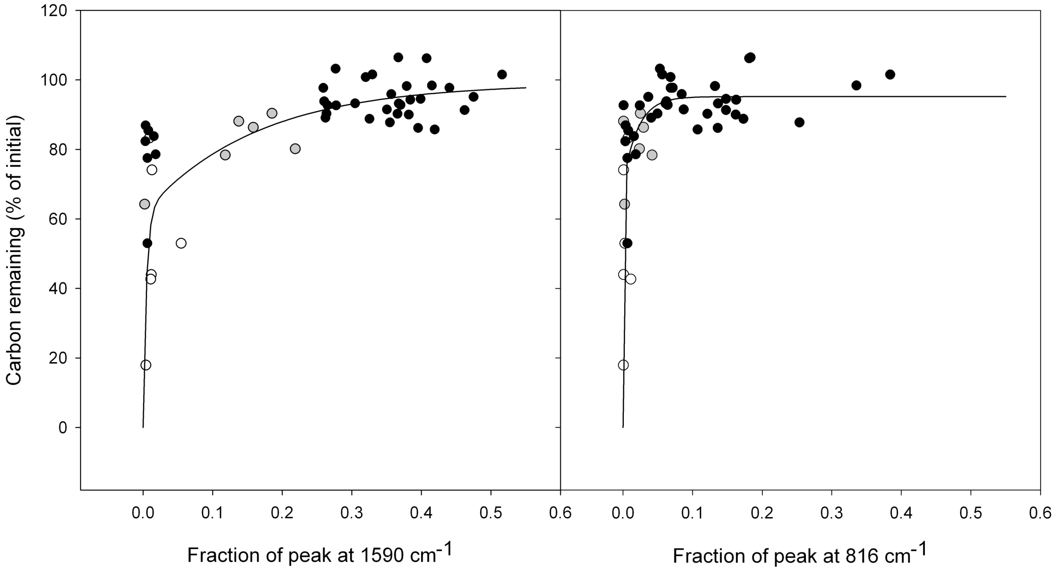


Figure 1.2. Left: Mean % C remaining vs. 1590 cm^{-1} fraction. $y = 61.4713*(1-e^{-217.6415*x})+37.5581*(1-e^{-6.1217*x})$, $R^2=0.71$. Right: Mean %C remaining vs. 814cm^{-1} fraction. $y = 69.89*(1-e^{-2545.1084*x}) +25.31*(1-e^{-48.0746*x})$, $R^2=0.53$. Both equations calculated excluding poultry data, although poultry data are included in figure. Grey circles indicate 300°C material while open circles indicate 60°C material.

After 5 months of incubation, the only significant effect of production temperature on C loss for the whole dataset is that the uncharred 60°C materials are distinguishable from the others, while there are significant differences between feedstocks, with poultry manure distinguishing itself from all other feedstocks, and significant differences between bull and oak BCs. However, after 3 years of incubation, we begin to see significant differences between production temperatures, with 300°C BCs experiencing significantly greater loss than 600°C BCs, while the only significant remaining feedstock-related difference is between poultry and three other BCs. Thus, the BC production temperature may play a more important role than feedstock in determining C loss over the longer term, particularly at high temperatures.

Relatively easily-degradable cellulose and hemicellulose pyrolyse at lower temperature ranges (220-400°C) than tough lignin (160-900°C) [26]. Thus, we might expect that BCs produced at relatively low temperatures retain some of the original pre-charring differences in cellulose and hemicellulose contents, which can explain both the differences in C loss between temperatures and the differences in C loss between feedstocks within low temperatures. Significant differences between feedstocks within a given temperature group are observed after 3 years for 60°C and 300°C BCs, but not for 350-550°C BCs. This may be because, beyond 300°C, if much of the cellulose and hemicellulose has been lost, the composition of the different BCs will have been normalized somewhat, selecting for compounds such as lignin. This would also explain why 300°C BCs show greater losses, because compounds that are more easily decomposed still remain. This is consistent with Nguyen and Lehmann's [14] study of four BCs, which showed significantly different C losses between BCs of different feedstocks produced at lower temperatures, but not between those produced at high temperatures.

These observations are supported by the FTIR spectra, which are relatively chemically similar across feedstocks within a given temperature, but are markedly different across temperatures within feedstocks, characterized by features such as the marked emergence of the aromatic C-H-associated wavenumbers around 450°C or the loss of the peak at the cellulose and hemicellulosic C-O-associated wavenumbers above 300°C. Although the correlation between C remaining and selected FTIR peaks explored in Figure 1.3 is instructive, it is not a perfect method of predicting C stability, since FTIR as applied in this study is not quantitative in a predictable way – *i.e.*, if the proportion of one kind of bond were to double in a BC upon heating, although we might expect its associated peak height to increase, we could not count on it to double exactly. However, this method of prediction may be an improvement over using production temperature as a predictor for C loss (Figure 1.2), since it begins to account for the non-linear chemical changes that take place upon heating organic matter [16].

The volatiles, ash, fixed carbon contents, and volatiles as a percentage of ash-free mass, have relatively good correlation coefficients with the fraction of C remaining – up to 0.57 (greater than that measured by Zimmerman [7] for volatile matter vs. total C mineralized). These data can be combined with the more detailed chemical data to provide a more comprehensive explanation for char stability.

1.4.2 BC properties and their association with C decomposition

Higher temperature BCs were generally characterized by a loss of aliphatic C-H, CH_2 and CH_3 groups in carbohydrates, hemicellulose, cellulose, and lignin, while the importance of aromatic C-H and C=C groups increased, as seen in both the FTIR and NMR analyses, and are consistent with previous analyses of charred organic matter [16, 21]. The compounds lost during these changes would be included the category designated as "volatiles", which decreased at higher temperatures, and were correlated with the associated FTIR wavenumber proportions, decreasing aromatic groups, and condensation of C groups. The remaining C groups appear to be increasingly condensed forms as temperatures increase, as indicated by the increasing NMR ^{13}C-benzene shift ($-\Delta\delta$) values [24].

According to Keiluweit *et al.*'s [16] BC categories, this would likely place the 300°C BCs in the "transition char" category, where lignin, cellulose, and hemicellulose still exert a large presence and total mass loss around 50%. The emergence of the trio of FTIR peaks around 816 cm^{-1}, mass loss, functional group loss, and increasing proportion of fixed carbon of the higher-temperature chars would categorize them as "amorphous chars" (likely 350-450°C) and "composite chars" (likely 450-600°C). These categorizations fit with the trends of C loss – losses do not appear to occur co-linearly with increasing temperature (the 300°C BCs are the only BCs that show significantly greater C loss than BCs of other temperature treatments).

The 300°C BCs retain 2925 cm^{-1} aliphatic C peaks, which have been found to decrease upon microbial incubation [27] indicating that these compounds are preferred by microbes as substrates. While we would expect the chemical differences in the higher-temperature BCs to translate into different degrees of C loss over time, the decomposition processes acting on the remaining non-pyrogenic carbon in the 300°C BCs likely occurs more rapidly than those affecting highly aromatic and condensed or protected carbon forms that dominate the higher-temperature BCs.

The initial BC properties have differing degrees of success at predicting C loss. The spectroscopic data are the most consistently relevant to C loss, but somewhat difficult to apply predictively and quantitatively for the reasons discussed above. While the proximate analysis provides relatively strong linear correlations, no correlations remain significant when the poultry BCs and original materials are excluded. However, this may be because three years of incubation was not enough for the higher temperature chars to experience significantly different C losses, while the variations in volatile, ash, and fixed C content are immediately apparent. Similarly, none of the NMR parameters correlated significantly with C loss, likely because the BCs selected for analysis did not include any 300°C BCs, which are the main source of variation in C loss. Applying more sensitive C measurement techniques may not solve this problem, as Zimmerman's [7] one-year study, using direct measurements of CO_2 loss yielded a similar correlation coefficient. Using longer incubation periods than three years begins to be impractical. While including materials produced at temperatures lower than 300°C could help to improve understanding of the effects of temperature on C loss and physical and chemical properties of BC, such materials would not be classified as "black carbon," and thus may be of questionable relevance to understanding the highest-temperature BCs.

1.4.3 Environmental applications: toward a BC stability metric

Some feedstocks reached a BC C: original C ratio of >1.0 by the end of 3 years of incubation (notably, the corn BCs, which reached ratios of 2.29-2.81). This “break even point” has important implications for the use of BC or “biochar” as a carbon management tool. For feedstocks where this ratio changes relatively little over time due to slow-decaying fresh materials, as with pine and oak, the C losses incurred immediately through char production leave the BC with a C debt for much longer than those feedstocks that experience rapid decay, such as corn stalks. Although production temperature is more important than feedstock for BC stability, feedstock becomes more important than production temperature in determining the C debt or credit ratio, since there is much more differentiation between decay rates of fresh materials, which depend solely on feedstock type, than there is between BCs. The C debt or credit ratio will continue to change as long as the fresh material and BC continue to decay at different rates, so the ratio and its rate of change give us a metric of the relative stabilities of the two materials. Using the 60°C incubation as a baseline, as we do here, must be understood in the context of what the true baseline conditions would be for a given feedstock. For example, if the fresh feedstock were not dried first and left to decay in a warm, moist field, we would expect that decay might be even faster than as measured here, making the C debt or credit ratio increase faster, while if they were dried and then kept in cool dry conditions, we would expect the ratio to take longer to reach the “break-even” point of 1.0. Hence, the ratios calculated here would have to be interpreted in the context of the true scenario.

1.5 Conclusions

In order to quantitatively assess the “recalcitrant fraction” of a given BC – *i.e.*, a fraction that would persist over hundreds to thousands of years – over a year of incubation under ideal conditions would likely be necessary, because significant C loss occurred in BCs after only 5 months. For low temperature BCs, original feedstock can be important in determining C loss, but for high temperature BCs, it is less important, for the range of feedstocks studied here. Furthermore, to evaluate the C debt or credit ratio of a BC, it is critical to monitor the decomposition of the biomass feedstock under baseline conditions in order to accurately evaluate at what point the ratio would be >1. For slow-decomposing organic matter such as oak or pine, this ratio quickly indicates that producing BC from materials that would otherwise decompose for the sake of C sequestration is unfavourable.

1.6 Supporting Information

Supporting data associated with this article follows.

SUPPORTING INFORMATION FOR CHAPTER 1 – BLACK CARBON DECOMPOSITION ACROSS PRODUCTION TEMPERATURES AS RELATED TO ITS INITIAL PROPERTIES

Table 1.S1. Mean percent C retention after five months[1]

	60°C^{B}	300°C^{aA}	350°C^{aA}	400°C^{aA}
Bull^{aC}	78.3*^{bB}	97.9 ^{abA}	97.1 ^{abAB}	98.6 ^{abA}
Corn^{abBC}	66.8* ^{bB}	92.9^{aA}	105.0 ^{aA}	105.3 ^{aA}
Dairy^{abBC}	76.2* ^{bB}	95.7 ^{aA}	95.9* ^{aAB}	99.3 ^{aA}
Oak^{cB}	96.4 ^{aA}	87.1* ^{aA}	90.4 ^{aAB}	94.4* ^{aAB}
Pine^{bcBC}	91.6* ^{aA}	103.6 ^{aA}	96.1 ^{aAB}	97.6 ^{aA}
Poultry^{dA}	49.5* ^{cC}	92.0* ^{aA}	84.1* ^{aB}	82.8*^{abB}
	450°C^{aA}	500°C^{aA}	550°C^{aA}	600°C^{aA}
Bull^{aC}	98.7 ^{abAB}	108.1 ^{aA}	109.4 ^{aA}	114.6 ^{aA}
Corn^{abBC}	101.0 ^{aA}	100.0 ^{aA}	106.0 ^{aA}	98.0 ^{aABC}
Dairy^{abBC}	102.2 ^{aA}	107.4 ^{aA}	103.3 ^{aA}	100.6 ^{aAB}
Oak^{cB}	93.8* ^{aAB}	93.3* ^{aA}	84.4 ^{aA}	87.0 ^{aBC}
Pine^{bcBC}	92.9 ^{aAB}	95.2*^{aA}	89.7 ^{aA}	95.4 ^{aABC}
Poultry^{dA}	85.3* ^{aB}	67.7* ^{bB}	88.7 ^{aA}	79.3* ^{abC}

1. Lowercase letters indicate significant differences within feedstock (pairwise comparisons, Tukey-Kramer HSD, a=0.05), uppercase letters represent significant differences within temperature (pairwise comparisons, Tukey-Kramer HSD, a=0.05), asterisks (*) indicate significant differences from 100% C (one-sided t-test, a=0.05), and ‡ indicates significant losses between 5 months and three years (t-test, $p<0.05$). Overall, significant differences between feedstocks and temperatures are indicated with capital letters when original materials are included and with lowercase letters when original materials are excluded (pairwise comparisons, Tukey-Kramer HSD, a=0.05).

Table 1.S2. Ratio of C remaining after (charring and) incubation – mean ratio of (BC): original materials (initial; 3 years)[1]

	300°C	350°C	400°C	450°C
Bull †	0.64;1.09*‡ †	0.53;1.04‡ †	0.48;0.91‡ †	0.45;0.76‡ †
Corn †	0.63;2.81*‡ †	0.49;2.49*‡ †	0.48;2.47*‡ †	0.46;2.50*‡ †
Dairy †	0.59;1.05‡ †	0.5;1.04‡ †	0.47;1.08*‡ †	0.46;0.98‡ †
Oak †	0.61;0.73	0.58;0.72 †	0.48;0.60	0.5;0.64‡ †
Pine	0.79;0.82	0.56;0.65‡	0.49;0.55	0.46;0.49‡
Poultry	0.9;1.35*‡ †	0.73;1.42*‡ †	0.58;1.18*‡ †	0.48;0.96‡ †
	500°C	550°C	600°C	
Bull †	0.42;0.76‡ †	0.47;0.84‡	0.42;0.85‡ †	
Corn †	0.48;2.29*‡ †	0.46;2.33*‡ †	0.46;2.54*‡ †	
Dairy †	0.44;0.92‡ †	0.43;0.91‡ †	0.43;1.04‡ †	
Oak †	0.45;0.55 †	0.49;0.66 †	0.41;0.55‡ †	
Pine	0.46;0.48	0.38;0.41	0.45;0.47‡	
Poultry	0.65;1.18‡ †	0.53;1.04‡	0.54;0.97‡	

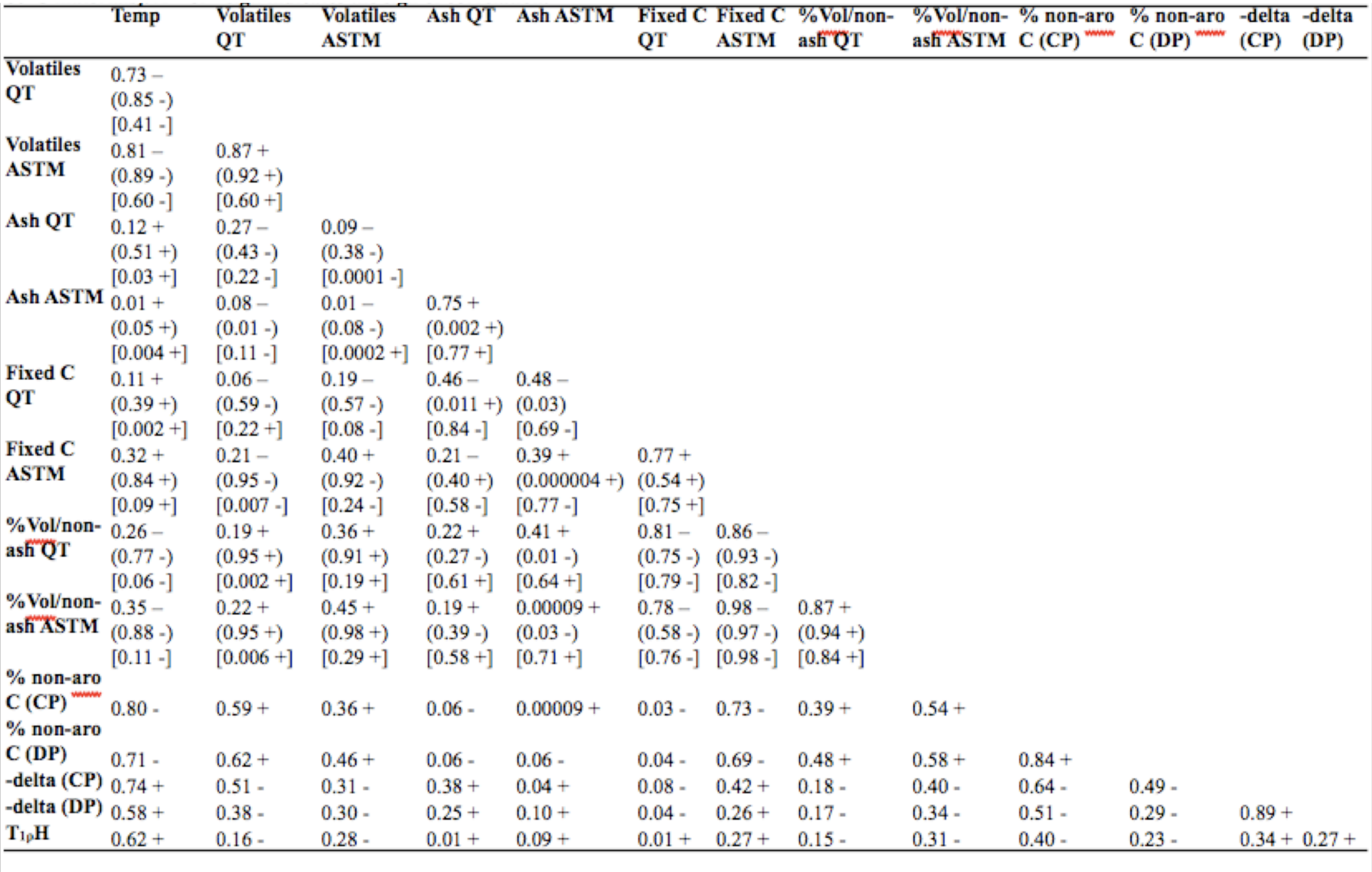
1. An asterisk (*) indicates a value significantly greater than 1.00, ‡ indicates significant difference between initial and 3-year values, and † indicates significant difference between 5-month (not shown) and 3-year values (t-tests, a=0.05).

Table 1.S3. Initial material properties

Feedstock	Temp (°C)	pH	C:N	Feedstock	Temp (°C)	pH	C:N
Bull	60	N/A	80.90	Oak	60	N/A	443.57
	300	8.17	43.64		300	4.48	336.50
	350	9.25	42.27		350	5.18	382.00
	400	9.81	48.79		400	6.21	402.50
	450	9.64	65.55		450	7.52	443.50
	500	9.54	59.64		500	7.95	435.50
	550	9.48	66.09		550	8.14	301.00
	600	9.54	78.33		600	7.9	451.00
Corn	60	N/A	83.29	Pine	60	N/A	847.08
	300	8.23	45.85		300	7.43	632.00
	350	9.39	50.33		350	5.31	695.00
	400	9.65	52.17		400	7.24	732.00
	450	9.44	56.42		450	7.38	813.00
	500	9.315	56.67		500	6.94	851.00
	550	9.38	75.67		550	5.2	845.00
	600	9.42	65.45		600	6.99	431.50
Dairy	60	N/A	46.67	Poultry	60	N/A	12.48
	300	8.58	34.50		300	8.94	10.63
	350	9.1	32.40		350	9.65	11.77
	400	9.55	48.79		400	9.82	14.59
	450	9.45	41.88		450	9.72	14.75
	500	9.58	44.69		500	10.03	16.35
	550	9.66	45.19		550	10.01	20.07
	600	9.72	45.38		600	10.33	22.08

Table 1.S4. – Total elemental analysis data – is part of the SI but is located in Appendix 2.1 due to its length.

Table 1.S5.1 Correlation coefficients for selected pairs of analytical properties across all feedstocks and temperatures (excluding poultry) [excluding 60°C materials]. A + or - sign indicates the sign of correlation.



	Temp	Volatiles QT	Volatiles ASTM	Ash QT	Ash ASTM	Fixed C QT	Fixed C ASTM	%Vol/non-ash QT	%Vol/non-ash ASTM	% non-aro C (CP)	% non-aro C (DP)	-delta (CP)	-delta (DP)
Volatiles QT	0.73 – (0.85 -) [0.41 -]												
Volatiles ASTM	0.81 – (0.89 -) [0.60 -]	0.87 + (0.92 +) [0.60 +]											
Ash QT	0.12 + (0.51 +) [0.03 +]	0.27 – (0.43 -) [0.22 -]	0.09 – (0.38 -) [0.0001 -]										
Ash ASTM	0.01 + (0.05 +) [0.004 +]	0.08 – (0.01 -) [0.11 -]	0.01 – (0.08 -) [0.0002 +]	0.75 + (0.002 +) [0.77 +]									
Fixed C QT	0.11 + (0.39 +) [0.002 +]	0.06 – (0.59 -) [0.22 +]	0.19 – (0.57 -) [0.08 -]	0.46 – (0.011 +) [0.84 -]	0.48 – (0.03) [0.69 -]								
Fixed C ASTM	0.32 + (0.84 +) [0.09 +]	0.21 – (0.95 -) [0.007 -]	0.40 + (0.92 -) [0.24 -]	0.21 – (0.40 +) [0.58 -]	0.39 + (0.000004 +) [0.77 -]	0.77 + (0.54 +) [0.75 +]							
%Vol/non-ash QT	0.26 – (0.77 -) [0.06 -]	0.19 + (0.95 +) [0.002 +]	0.36 + (0.91 +) [0.19 +]	0.22 + (0.27 -) [0.61 +]	0.41 + (0.01 -) [0.64 +]	0.81 – (0.75 -) [0.79 -]	0.86 – (0.93 -) [0.82 -]						
%Vol/non-ash ASTM	0.35 – (0.88 -) [0.11 -]	0.22 + (0.95 +) [0.006 +]	0.45 + (0.98 +) [0.29 +]	0.19 + (0.39 -) [0.58 +]	0.00009 + (0.03 -) [0.71 +]	0.78 – (0.58 -) [0.76 -]	0.98 – (0.97 -) [0.98 -]	0.87 + (0.94 +) [0.84 +]					
% non-aro C (CP)	0.80 -	0.59 +	0.36 +	0.06 -	0.00009 +	0.03 -	0.73 -	0.39 +	0.54 +				
% non-aro C (DP)	0.71 -	0.62 +	0.46 +	0.06 -	0.06 -	0.04 -	0.69 -	0.48 +	0.58 +	0.84 +			
-delta (CP)	0.74 +	0.51 -	0.31 -	0.38 +	0.04 +	0.08 -	0.42 +	0.18 -	0.40 -	0.64 -	0.49 -		
-delta (DP)	0.58 +	0.38 -	0.30 -	0.25 +	0.10 +	0.04 -	0.26 +	0.17 -	0.34 -	0.51 -	0.29 -	0.89 +	
$T_{1\rho}H$	0.62 +	0.16 -	0.28 -	0.01 +	0.09 +	0.01 +	0.27 +	0.15 -	0.31 -	0.40 -	0.23 -	0.34 +	0.27 +

Table 1.S5.2 Correlation coefficients for FTIR parameters and selected other analytical properties across all feedstocks and temperatures (excluding poultry) [excluding 60°C materials]. A + or - sign indicates the sign of correlation.

	Temp	Volatiles QT	Volatiles ASTM	Ash QT	Ash ASTM	Fixed C QT	Fixed C ASTM	%Vol/ non-ash QT	%Vol/ non-ash ASTM	% non-aro C (CP)	% non-aro C (DP)	-delta (CP)	-delta (DP)	$T_{1\rho}H$
1590	0.40 +	0.21 –	0.41 –	0.12 –	0.31 –	0.61 +	0.82 +	0.71 -	0.84 -					
	(0.82 +)	(0.75 -)	(0.75 -)	(0.45 +)	(0.07 +)	(0.33 +)	(0.68 +)	(0.68 -)	(0.73 -)					
	[0.17 +]	[0.002 -]	[0.21 -]	[0.44 -]	[0.55 -]	[0.55 +]	[0.76 +]	[0.63 -]	[0.78 -]	0.23 -	0.28 -	0.17 +	0.14 +	0.22 +
816	0.39 +	0.22 –	0.36 –	0.007 –	0.14 –	0.23 +	0.53 +	0.40 -	0.51 -					
	(0.54 +)	(0.41 -)	(0.43 -)	(0.36 +)	(0.02 -)	(0.12 +)	(0.53 +)	(0.40 -)	(0.48 -)					
	[0.42 +]	[0.20 -]	[0.40 -]	[0.05 -]	[0.21 -]	[0.17 +]	[0.48 +]	[0.33 -]	[0.45 -]	0.68 -	0.58 -	0.57 +	0.33 +	0.39 +
1700	0.04 –	0.006 –	0.001 –	0.02 –	0.02 –	0.05 +	0.02 +	0.04 -	0.02 ns -					
	(0.01 +)	(0.10 -)	(0.04 -)	(0.007 +)	(0.006 -)	(0.12 +)	(0.05 +)	(0.07 -)	(0.04 -)					
	[0.44 -]	[0.45 +]	[0.23 +]	[0.38 -]	[0.32 -]	[0.17 +]	[0.07 +]	[0.08 -]	[0.06 -]	0.31 +	0.55 +	0.47 -	0.32 -	0.21 -
2925	0.29 –	0.09 +	0.19 +	0.15 +	0.36 +	0.46 –	0.62 –	0.48 +	0.60 +					
	(0.65 -)	(0.58 +)	(0.54 +)	(0.40 -)	(0.001 -)	(0.22 -)	(0.57 -)	(0.54 +)	(0.56 +)					
	[0.17 -]	[0.01 +]	[0.15 +]	[0.32 +]	[0.49 +]	[0.44 -]	[0.63 -]	[0.50 +]	[0.61 +]	0.22 +	0.24 +	0.30 -	0.21 -	0.0004 +
1460	0.55 –	0.33 +	0.40 +	0.01 –	0.001 +	0.12 –	0.24 –	0.17 +	0.27 +					
	(0.72 -)	(0.66 +)	(0.69 +)	(0.34 -)	(0.12 -)	(0.34 -)	(0.58 -)	(0.62 +)	(0.64 +)					
	[0.40 -]	[0.31 +]	[0.45 +]	[0.003 -]	[0.0008 -]	[0.02 -]	[0.08 -]	[0.05 +]	[0.11 +]	0.23 +	0.44 +	0.34 -	0.17 -	0.05 -
1424	0.55 –	0.64 +	0.66 +	0.13 –	0.03 –	0.07 –	0.20 –	0.18 +	0.23 +					
	(0.72 -)	(0.67 +)	(0.69 +)	(0.39 -)	(0.10 -)	(0.31 -)	(0.59 -)	(0.59 +)	(0.65 +)					
	[0.28 -]	[0.21 +]	[0.32 +]	[0.01 -]	[0.002 -]	[0.001 -]	[0.05 -]	[0.03 +]	[0.07 +]	0.30 +	0.25 +	0.30 -	0.26 -	0.26 -
1374	0.18 –	0.28 +	0.22 +	0.09 –	0.02 –	0.01 –	0.05 –	0.04 +	0.05 +					
	(0.23 -)	(0.26 +)	(0.22 +)	(0.10 -)	(0.008 +)	(0.17 -)	(0.27 -)	(0.26 +)	(0.27 +)					
	[0.10 -]	[0.27 +]	[0.09 +]	[0.33 -]	[0.12 -]	[0.20 +]	[0.03 +]	[0.07 -]	[0.04 -]	0.29 +	0.10 +	0.14 -	0.06 -	0.13 -
1048	0.58 –	0.82 +	0.71 +	0.19 -	0.05 –	0.07 –	0.19 –	0.18 +	0.21 +					
	(0.73 -)	(0.84 +)	(0.74 +)	(0.41 -)	(0.03 -)	(0.47 -)	(0.72 -)	(0.74 +)	(0.74 +)					
	[0.16 -]	[0.25 +]	[0.20 +]	[0.06 -]	[0.02 -]	[0.01 +]	[0.008 -]	[0.001 +]	[0.009 +]	0.35 +	0.26 +	0.08 -	0.001 -	0.03 -

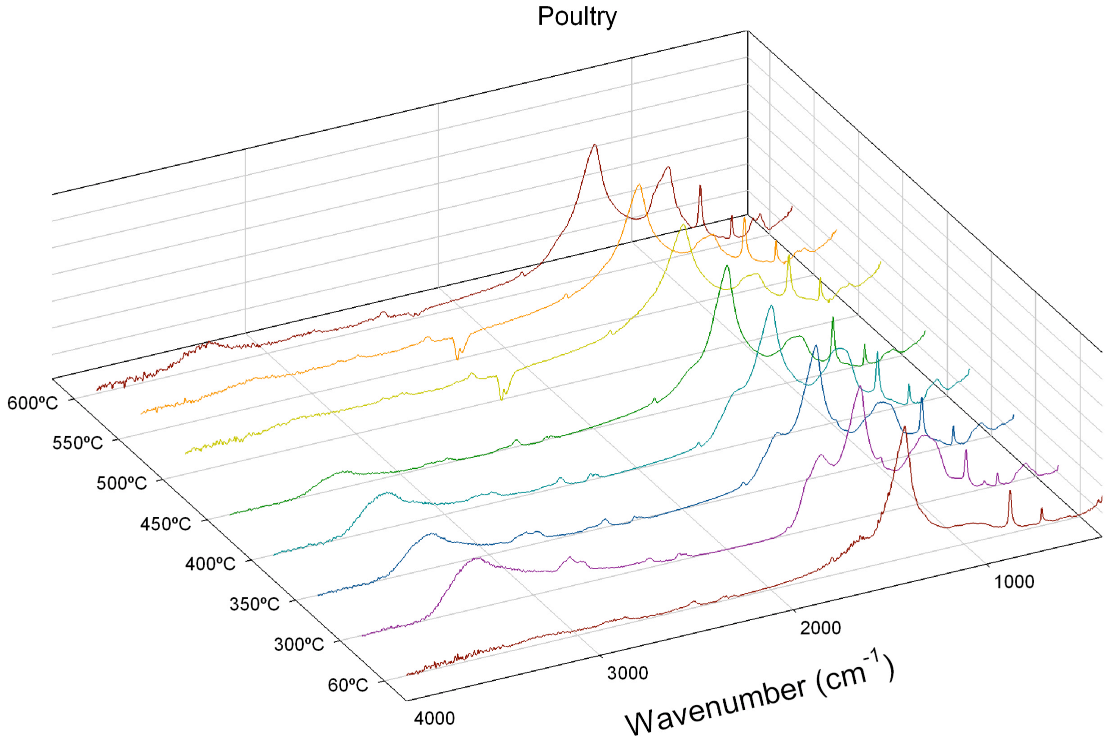


Figure 1.S1. FTIR spectra for poultry manure with sawdust feedstock across temperatures

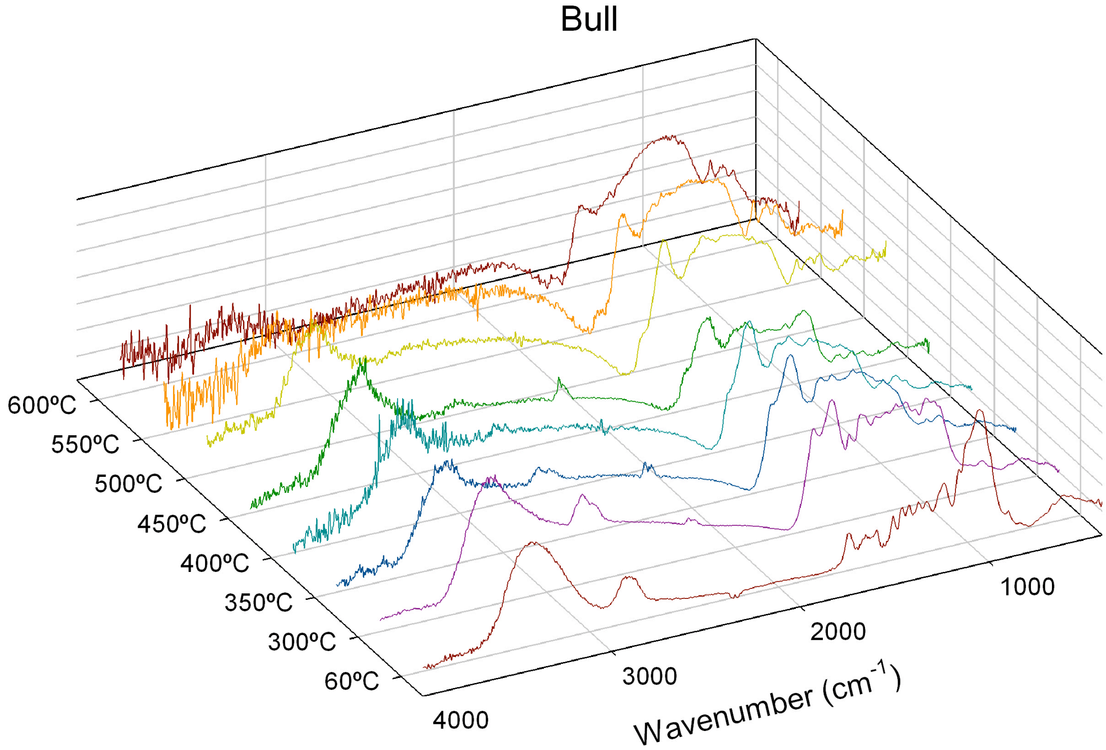


Figure 1.S2. FTIR spectra for bull manure with sawdust feedstock across temperatures

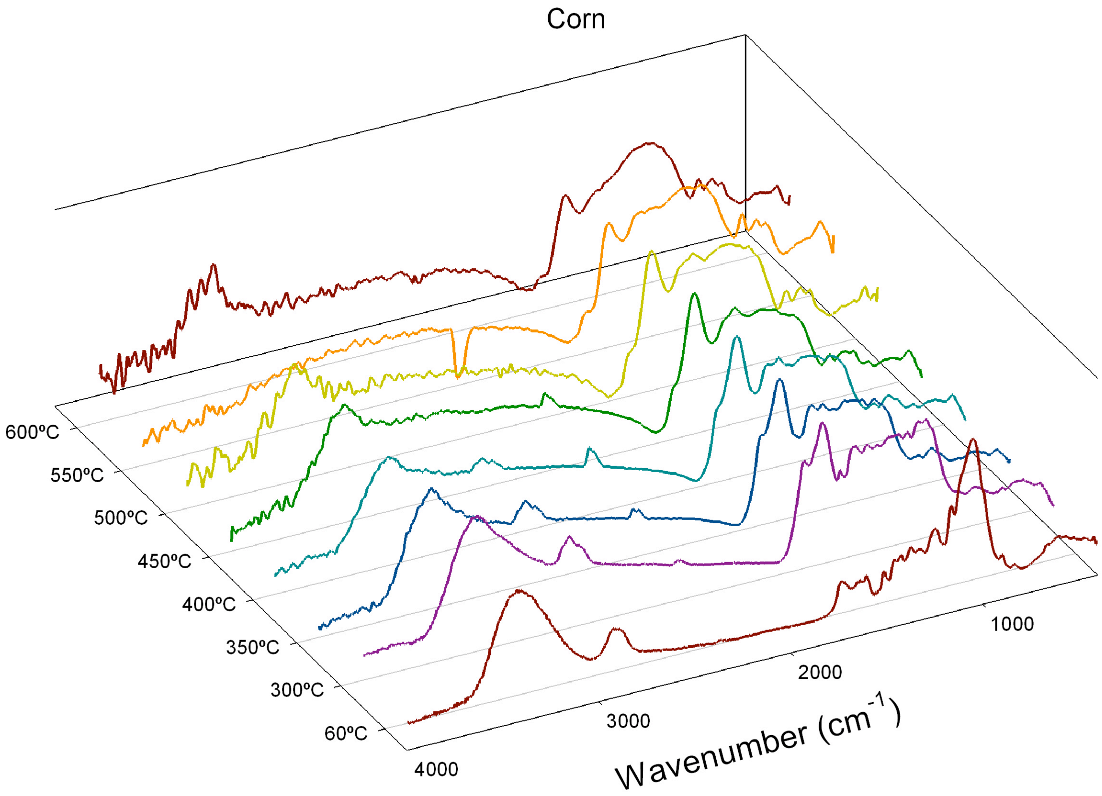


Figure 1.S3. FTIR spectra for corn stover feedstock across temperatures

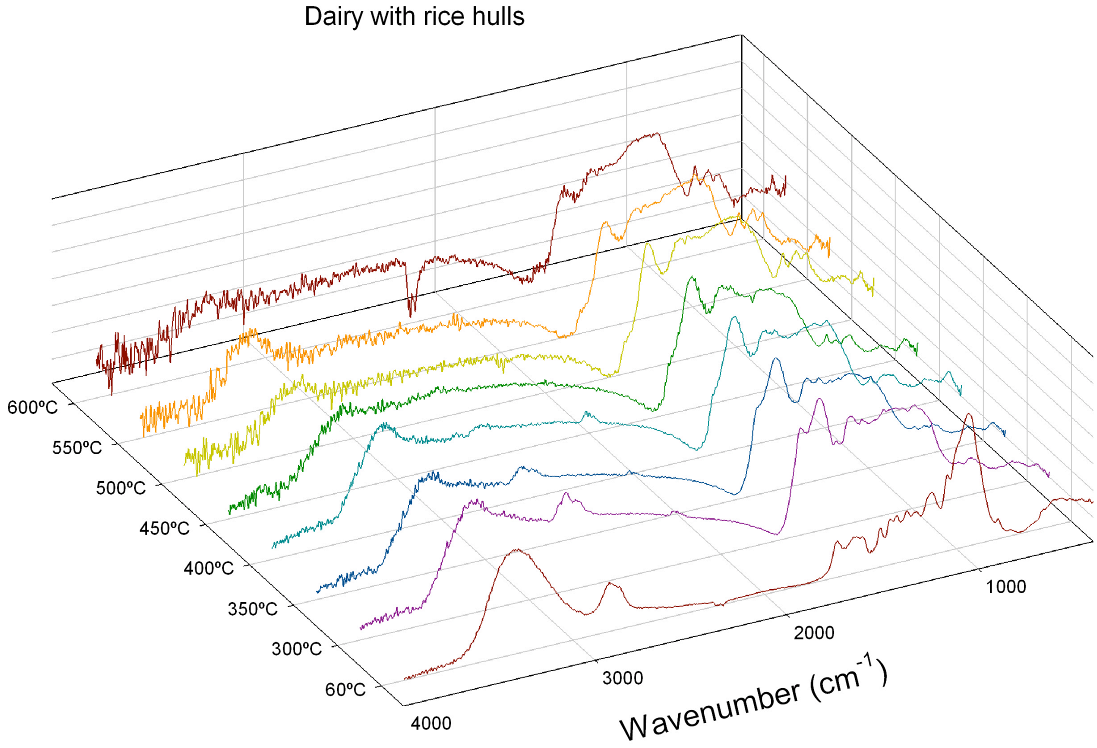


Figure 1.S4. FTIR spectra for dairy manure with rice hulls feedstock across temperatures

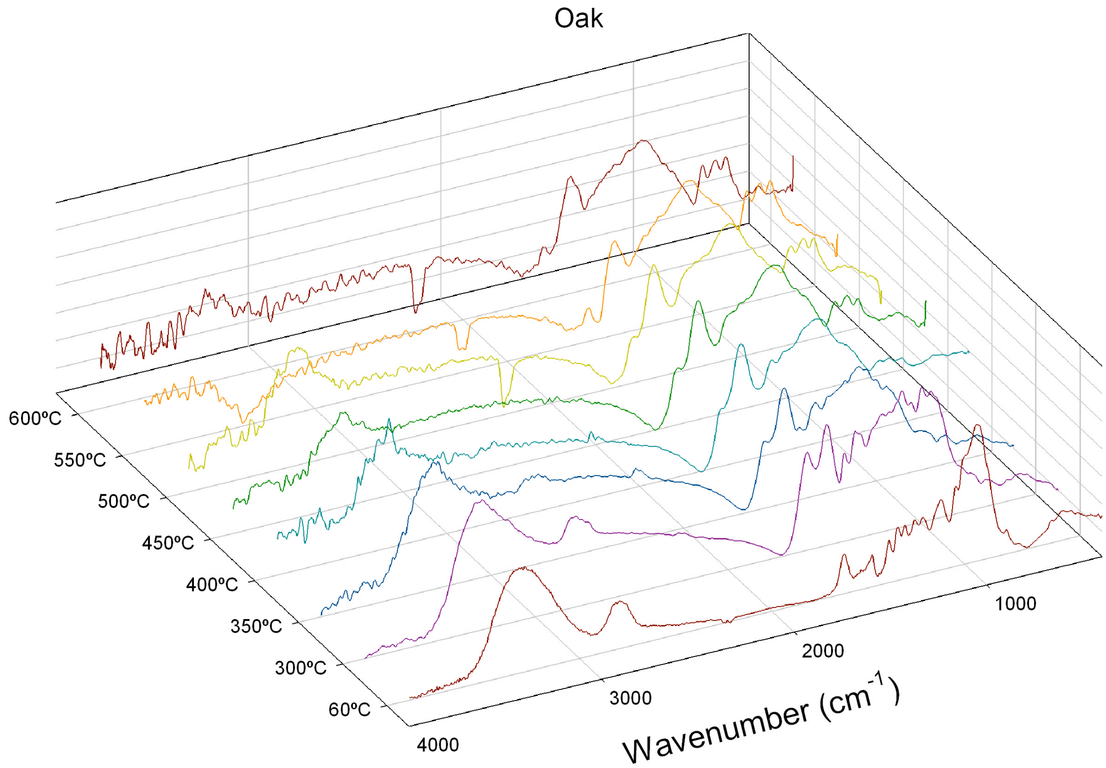


Figure 1.S5. FTIR spectra for oak feedstock across temperatures

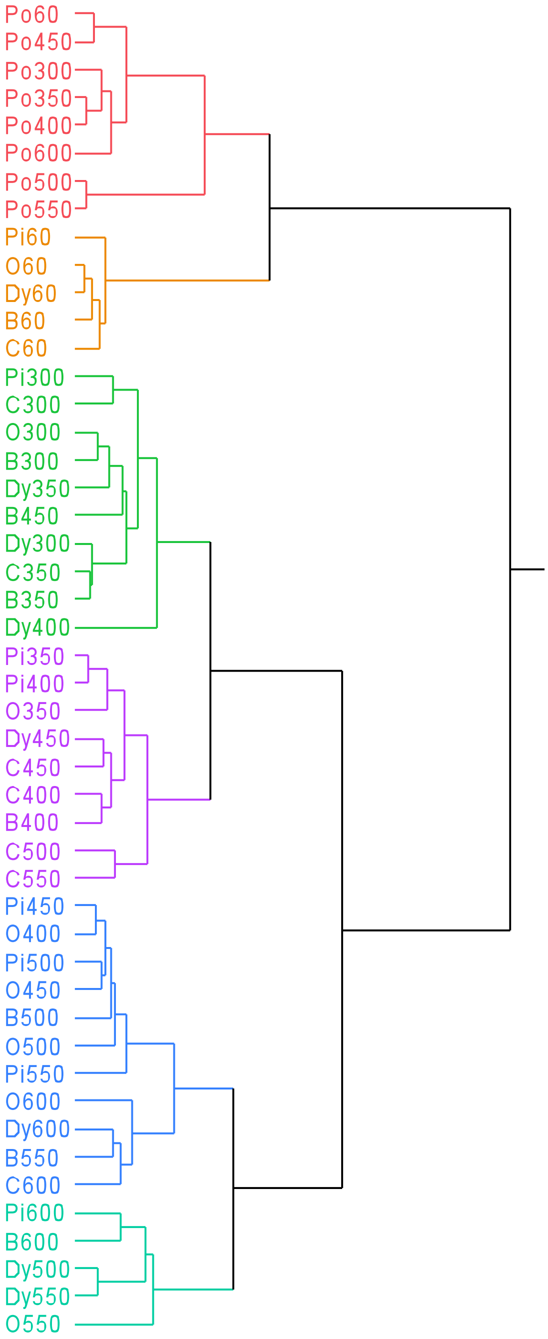


Figure 1.S6. Dendrogram showing FTIR spectra similarity based on Ward's hierarchical clustering method. B=bull manure with sawdust, C=corn stover, Dy=dairy manure with rice hulls, O=oak, Pi=pine, and Po=poultry manure with sawdust, while numbers represent charring or drying temperature.

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CHAPTER 2

CLIMATE CHANGE IMPACT OF A BIOCHAR COOK STOVE IN WESTERN KENYAN FARM HOUSEHOLDS: SYSTEM DYNAMICS MODEL ANALYSIS[2]

Abstract

Cook stoves that produce biochar as well as heat for cooking could help mitigate indoor air pollution from cooking fires in addition to enhancing local soils, while their potential reductions in carbon emissions and increase in soil carbon sequestration could offer access to carbon market financing. We use system dynamics modelling to: (i) investigate the climate change impact of prototype and refined biochar-producing pyrolytic cook stoves and improved combustion cook stoves in comparison to conventional cook stoves; (ii) assess the relative sensitivity of the stoves to key parameters; (iii) quantify the effects of different climate change impact accounting decisions. Simulated reductions in greenhouse gas (GHG) impact from a traditional 3-stone cook stove baseline range between 2.56-4.63 tCO_2e/household/year for the improved combustion stove and 2.58-5.80 tCO_2e/household/year for the pyrolytic stoves, of which biochar directly accounts for 14-50%. The magnitude of these reductions is about twice as sensitive to baseline wood fuel use and the fraction of non-renewable biomass (fNRB) of off-farm wood that is used as fuel as to farm age/soil degradation status or stability of biochar. Reductions in GHG impact decrease if a household must access non-renewable fuel sources. Stoves with higher wood demand are less sensitive to changes in baseline fuel use and rely on biochar for a greater proportion of their reductions.

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2.1 Introduction

Half of the global population relies on biomass fuels for energy [1]. Improved cook stove projects in developing countries have been promoted for decades [2, 3], driven alternately or jointly over the years by the desires to improve health by decreasing indoor air pollution from cooking and to limit forest degradation and deforestation while decreasing the burden on those who collect the biomass fuels – usually women [4]. Recently, a third motivation for improved cook stove projects has gained prominence: the potential of improved cook stoves to mitigate climate change [5].

Inefficient burning of biomass in cook stoves results in a high greenhouse gas (GHG) emission to energy ratio for the fuel used [5]. While these activities contribute less than 0.5% of global GHG emissions [6], biofuel use contributes around 20-35% of global black carbon emissions [7, 8], which have potent warming effects, although they are currently unregulated by the Kyoto Protocol [9]. Climate change mitigation is a motivation not only because of the degree to which cook stoves contribute to global warming, but also because carbon credits could help finance these projects, enabling their important non-climate benefits as well.

In order to access carbon financing for small-scale projects using improved cook stoves, the climate impact of the stoves' introduction must be calculated, which can be complex [10, 11]. Methodologies for improved cook stove projects have been developed [12, 13], which could apply to many different types of improved cook stoves [4, 14]. Although extensive research has been conducted on the mitigation potential of improved stove systems in Mexico [5, 10, 14, 15], this research was limited to direct stove impacts, without examining dynamics and feedbacks within the system. Cook stoves that produce biochar as well as cooking energy are a relatively recently developed technology, and have yet to be rigorously investigated for their climate change mitigation potential [16-18].

Biochar is the carbon-rich material produced when biomass is heated to high temperatures under anoxic or oxygen-limited conditions (pyrolysis) [19], and can be used as a soil amendment to improve fertility in degraded soils [20]. The term “biochar” is used here to distinguish the material from charcoal created for fuel, and to denote its particular application in carbon-sequestering and emission-reducing projects as a soil amendment. Pyrolysis cook stoves are loaded with biomass to be charred by a primary combustion source under oxygen-limited conditions, and combust the gases released as charring takes place, producing energy for cooking as well as biochar [16, 18]. These cook stoves add another layer of complexity to the climate impacts of the system due to: (i) the possible effects of biochar applied to soil on crop yields, (ii) the stabilization of the relatively labile C from fresh biomass as biochar, and (iii) possible changes in the sources of biomass that can be used as fuel.

This study uses system dynamics simulation modelling to: (i) investigate the full climate change impact of biochar-producing cook stoves and improved combustion cook stoves in comparison to conventional cook stoves, (ii) assess the relative sensitivity of the stoves to key parameters, and (iii) quantify the effects of different climate change impact accounting decisions.

2.2 Methods

2.2.1 Modelled system

Our modelled system is a rural farm household in the highlands of western Kenya (see Figure 2.S1 in Supporting Information [SI]). The region is characterised by common use of traditional 3-stone biomass cook stoves and declining biomass fuel availability, as evidenced by the decline of the nearby Kakamega and Nandi forests

[21, 22] and the observed occasional use of green wood for cooking fuel. Although the forests' decline is likely due to a wide range of factors, including harvest for charcoal or timber and land-clearing for agriculture or settlement, it does result in increased pressure on households to gather sufficient fuel for cooking [23, 24]. Farm households primarily grow maize, but some also grow leafy greens (sukuma-wiki) or banana trees, among other minor crops. Livestock such as poultry or cows are also present on many farms, but are generally not the primary agricultural activities. The region is also marked by declines in maize yields over the time since farms were converted from primary forest. This decline has been shown to be mitigated by the application of biochar to soils, increasing yields [20].

2.2.2 Model structure

We employed a system dynamics modelling approach to determine the GHG impact of the introduction of improved biomass cook stoves using either pyrolysis or combustion technology to a western Kenyan farm household. System dynamics models are systems of differential equations that represent the stock-flows and feedback structure of a system [25, 26]. The system of equations is solved using numerical integration with a specified calculation interval using Vensim ® simulation software (Ventana Systems, Inc. [27]). A system dynamics model is appropriate for our research objectives because it allows us to explicitly account for the stock-flow feedback dynamics of the system in response to the introduced cook stoves. The household level is ideal because we have robust data available at this fine scale, and because it would be relatively straightforward to extrapolate to larger scales (village, region).

Our model consists of four interlinked modules: on-farm production, soil carbon, cook stove fuel use and emissions, and GHG impact (Figure 2.S2). (The term

GHG impact is used to highlight the inclusion of changes in soil C and biochar C as well as changes in direct stove emissions.) The model is called Stove Impact on Climate Change Tool (SImpaCCT).

2.2.3 Farm production module

The farm production module (Figure 2.S3) models the production of on-farm biomass, including maize stover (*Zea mays*), banana leaves (*Musa sp.*), sukuma-wiki (*Brassica oleracea*) clippings, and mixed wood harvest. Production rates of banana leaves, sukuma-wiki, and on-farm wood are based on on-farm biomass assessments conducted by Torres in 2008 [16]. Only the portion of each crop that is currently unused or the mean annual incremental (MAI) tree growth is considered to be available. Maize stover production was derived from 5 years of field studies on a group of 42 farms in western Kenya during short and long rain seasons [20]. Stover production decreases with increasing farm age, as soils become increasingly degraded. An average of 25% of stover is devoted to other uses, such as animal feed, while the remainder is left on the field, which helps to prevent erosion and return soil carbon and other nutrients to the soil [28]. Experimental results show that maize grain yield increases by an average of 120% as biochar is applied. The degree to which this response is shown increases as both the total biochar in the soil and farm age increase. (The farm production module is described more extensively in the SI).

2.2.4 Fuel use and stove emissions module

2.2.4.1 Fuel use and stove emissions module overview

The fuel use and stove emissions module (Figure 2.S7) determines how much fuel is required, which sources of biomass are used for fuel, how much GHG emissions are produced, and how much biochar is produced. The three modelled stoves are the traditional 3-stone cook stove, a biochar-producing pyrolytic cook stove, and another improved cook stove which is modelled primarily after “rocket stoves”, which are based on improved combustion efficiency, reduced smoke output, and increased heat transfer efficiency, and are often made of metal with a central combustion chamber and some form of insulation [4]. The stove in SImpaCCT would be analogous to other types of wood-fuelled improved combustion cook stoves.

2.2.4.2 Fuel demand

Baseline fuel demand is based on the measured per-capita daily fuel use for a 3-stone stove (described in the SI), determined to be 1.95 kg dry wood/person/day, which is very close to that reported in Yevich and Logan [29], which is 1.89 kg dry wood/person/day. Mean household size was measured at 6.7 people, with adult-equivalent weighting assigned as described in Bailis *et al*. [30] and the SI.

Fuel use relative to a 3-stone cook stove was calculated based on water boiling tests (WBTs) for the improved combustion stove [31]. We note that WBTs have been demonstrated to be problematic in terms of accurately predicting combustion efficiency under actual usage [10, 32], but found the numbers generated using this method to be within the range of other improved cook stoves [14]. Relative fuel use for the pyrolytic cook stove was calculated based on kitchen cooking tests with a prototype pyrolytic stove using sawdust, corn cobs, and corn stover as fuel [16] as compared to a 3-stone cook stove, normalized by mass of food cooked. The values for a refined pyrolytic stove were generated by using the same ratio of fuel for primary combustion to fuel for packing the stove and the same fraction of C converted to biochar as for the prototype stove, but determining total fuel demand assuming that the energy derived from the remaining C is equivalent to that of a gasifier stove [31]. We are currently limited by a lack of comprehensive field and lab testing of pyrolytic stoves, but these approximations provide us with a possible range (Table 2.S2).

2.2.4.3 Fuel use

For all stoves, biomass for household primary combustion is assumed to be used preferentially in this order: (i) on-farm woody biomass, (ii) off-farm woody biomass. These assumptions are plausible, as households have been observed to use wood from their own farms as fuel. Using the on-farm biomass before the off-farm biomass is also consistent with the assumption that people would gather biomass that is closer and more accessible first. The pyrolysis stove also uses secondary combustion, for which biomass is used preferentially in this order: (i) on-farm herbaceous biomass, (ii) on-farm woody biomass, (iii) off-farm woody biomass. The availability of on-farm herbaceous biomass may be limited by demand for other uses, such as feed for animals.

2.2.4.4 Stove emissions

For the improved combustion and 3-stone stoves, all C in fuel biomass is converted to C in emissions during combustion, while in the pyrolysis stove, 59.5% of the C is retained as biochar [16]. For all stoves, the C released in fuel biomass is divided between emissions of CO_2, CO, CH_4, particulate black C, or elemental C (EC), and particulate white/clear/brown C, or organic C (OC) based on CO:CO_2 ratios and other PICs:CO ratios (as described in the SI). N_2O emissions are expected to be negligible and are neglected [31, 33].

2.2.5 Soil carbon module

The soil C module models the biochar and non-biochar soil organic C (SOC) dynamics of the farm's maize plots. SOC is modelled in four pools – residue C on soil (which has a labile and recalcitrant fraction), free light SOC, intra-aggregate SOC, and organomineral SOC (Figure 2.S8). This structure has similarities to the pool-based approach used in the CENTURY model [34] and the RothC model [35]. However, we chose to develop a new model rather than using adapting extant ones in order to represent black carbon as a separate fraction and to base pool types on measurable SOC fractions. The model was parameterized using the measured maize stover production data from 2004-2009 [20], reported residue retention rates from field surveys (75%), and SOC stocks over time from the free light, intra-aggregate, and organomineral fractions [36] (described further in the SI). All maize stover that is not harvested (as described in *2.2.3 Farm Production Module*) is assumed to remain on the maize plots as residue C on the soil surface.

We assume that all biochar produced is applied to the maize plots, although it is possible that it would be first applied to the "kitchen gardens", as is common practice with fire ashes. It is modelled as being composed of two fractions, one more labile (10-50%) and one more recalcitrant (50-90%). The labile fraction is integrated immediately into the free light SOC fraction, where it behaves as the non-biochar SOC does, decaying and cycling relatively rapidly. The recalcitrant fraction of biochar decays very slowly, with a mean residence time of 100 to 1000 years.

Data were not available on the SOC of the farm plots other than for maize, so SOC was not modelled for them. That is, we assume that no significant changes occur to the soil C stocks for other plots as a result of their biomass being used as fuel.

2.2.6 GHG impact module

The GHG impact module calculates the size of the C stocks, accounts for the form of the C, and determines the net impact for each cook stove scenario. The difference between the baseline (here, the three-stone cook stove) scenario and the improved cook stove scenario provides a measure of the reduction in GHG impact.

For the maize field SOC and maize stover used for fuel, all C flows are directly traced, which is appropriate for measuring total GHG impact. An increase in stove emissions results in an increase in net impact, whereas any increase in terrestrial storage results in a decrease in net impact. However, this approach is only possible when all C stocks and flows are known and traced. In the case of the wood biomass, we do not model changes in the forest C stock directly. Instead, we assess whether the harvest and use of a given biomass is sustainable [5, 12, 37]. We consider two extreme scenarios. In the sustainable, or renewable scenario, biomass C can be gathered from a stock in perpetuity, and the stock will both be replenished, and also would not have increased beyond its stable level if the gathering had not taken place. This would be similar to a climax forest that is being managed sustainably. In the unsustainable, or non-renewable scenario, biomass C that is gathered from a stock immediately depletes the stock, and the stock will never be replenished. This would be similar to rapid deforestation. Neither of these situations is likely to be an entirely accurate representation for the Kenyan household considered here, but these two extreme cases provide a sense for the importance of harvest sustainability to our findings. A number describing the degree of harvesting unsustainability (referred to as the fraction of non-renewable biomass – fNRB) allows us to explore scenarios between these two extremes.

In SImpaCCT, the on-farm wood biomass and the non-maize biomass produced on the farm are modelled as being sustainable (fNRB=0), while the off-farm wood biomass is set initially at fNRB = 1 – completely unsustainable. This value is consistent with the status of the Kakamega-Nandi forests, which have been deforested at rapid rates, despite some degree of official protection [3, 21, 22].

Under the unsustainable scenario, because the harvest is completely unsustainable, no C that is harvested and then released as emissions will be replaced as the forest grows back. Thus, all emissions from unsustainably harvested C are considered to increase the stock of GHGs in the atmosphere. Similarly, on a C basis, removing wood C from the forest unsustainably and turning it into biochar C does not immediately result in a net change in atmospheric stocks of C – it simply changes the form and location of the terrestrial C stock. Thus, biochar produced from unsustainably harvested wood results in no net GHG impact, until it is mineralized to CO_2, at which time, it is considered to result in a net GHG increase in the atmosphere, as described above. (This approach is investigated in more detail in the results and discussion.)

In the sustainable scenario, because the harvest is completely renewable, every C atom harvested and then released as a GHG is paired with a C atom in CO_2 that is newly fixed by photosynthesis. Thus, for CO_2 emissions, the net impact is zero, while for other products of incomplete combustion (PICs) that contain one C atom, the net impact is their global warming potential (GWP) minus the impact of the CO_2 molecule that is fixed by plants (referred to as the renewable GWP, or rGWP [see Appendix 2.1 for explanatory article]). Similarly, when biomass is harvested and used to produce biochar, there is an increase in the terrestrial biochar stocks, while the terrestrial biomass stocks do not change, because they are being harvested sustainably. Thus, the net effect will be that atmospheric C stocks in the form of CO_2 are decreased by an amount equal to the amount of C in the produced biochar. The GWPs of modelled stove emissions, as well as their status in the Kyoto Protocol are shown in Table 2.S4. The equations used in the GHG impact module are described in detail in the SI.

2.2.7 Model scenarios

2.2.7.1 GHG impact deviation from baseline

To explore the possible magnitude of the net GHG deviation from baseline, the outcomes were simulated for 100 years with model parameters representing a 30-year old farm, while varying the MRT of passive biochar between 100-1000 years, the proportion of maize residues gathered between 0.25-0.50, and the fNRB of off-farm wood between 0.5-1. A thirty year-old farm is around the median age of the studied farms, and would have been farmed long enough for significant soil degradation to take place [20]. One hundred years provides a time horizon to investigate the long-term dynamics of the biochar. For simplicity, other household dynamics that would change over this time horizon, such as family size or changes in cooking technology, are ignored.

2.2.7.2 Sensitivity analysis

Because some parameter values are not known with certainty or may differ in alternative settings, we conducted sensitivity analyses on selected parameters to explore which parameters most influence system behavior. The default scenario is a 30 year-old farm (as a proxy for the degree of soil degradation), where 1.9 kg dry wood/capita/day is used and the off-farm fNRB is 1. 25% of maize stover is gathered (25% goes to non-fuel uses). The biochar that is produced has a passive fraction of 80%, with a MRT of 600 years, and has a maximum impact on maize yields of 2.3 times the yields without biochar. These parameters are varied as shown in Table 2.1.

Table 2.1. Model parameter variation for sensitivity analysis

Parameter	Range	Default Scenario
A. MRT for passive biochar C	100-1000 years	600 years
B. Passive BC C fraction	0.5-0.9	0.8
C. Impact of BC on maize yields	1.0-2.3 times yield with no BC	2.3
D. Fraction of maize stover gathered	0.25-0.75	0.25
E. Baseline fuel use	1.0-3.0 kg dry wood/capita/day	1.9 kg dry wood/capita/day
F. fNRB off-farm wood	0.0-1.0	1.0

2.2.7.3 Policy analysis

Alternate ways of approaching the accounting of GHG impacts can produce different estimates of the effects of introducing an improved cook stove. Although our default scenario examines only gases regulated under the Kyoto protocol, other stove emissions are known to have an effect on the climate. We therefore also investigate the effect of excluding (default) or including non-Kyoto emissions.

A second policy decision is how to account for biochar that is produced from unsustainably harvested wood. We explore the effects of considering it to represent no net change in terrestrial C stocks (default) or to represent an immediate loss of C.

2.3 Results and discussion

2.3.1 GHG impact deviation from baseline

The simulated reductions in GHG impact over 100 years range between mean annual reductions of 2.58-4.74 tCO_2e/household/year for the prototype pyrolytic stove, 3.33-5.80 tCO_2e/household/year for the refined pyrolytic stove, and 2.56-4.63 tCO_2e/household/year for the improved combustion stove (Figure 2.1).

All reductions achieved by the non-biochar improved cook stove are due to decreased emissions. For the pyrolysis stove, reductions in gaseous emissions made up much of the reductions, although biochar production and increases in SOC both play substantial roles, particularly in the minimum deviation from baseline scenarios. We compared our values to those in Johnson *et al*. [5] for Kyoto emissions from improved

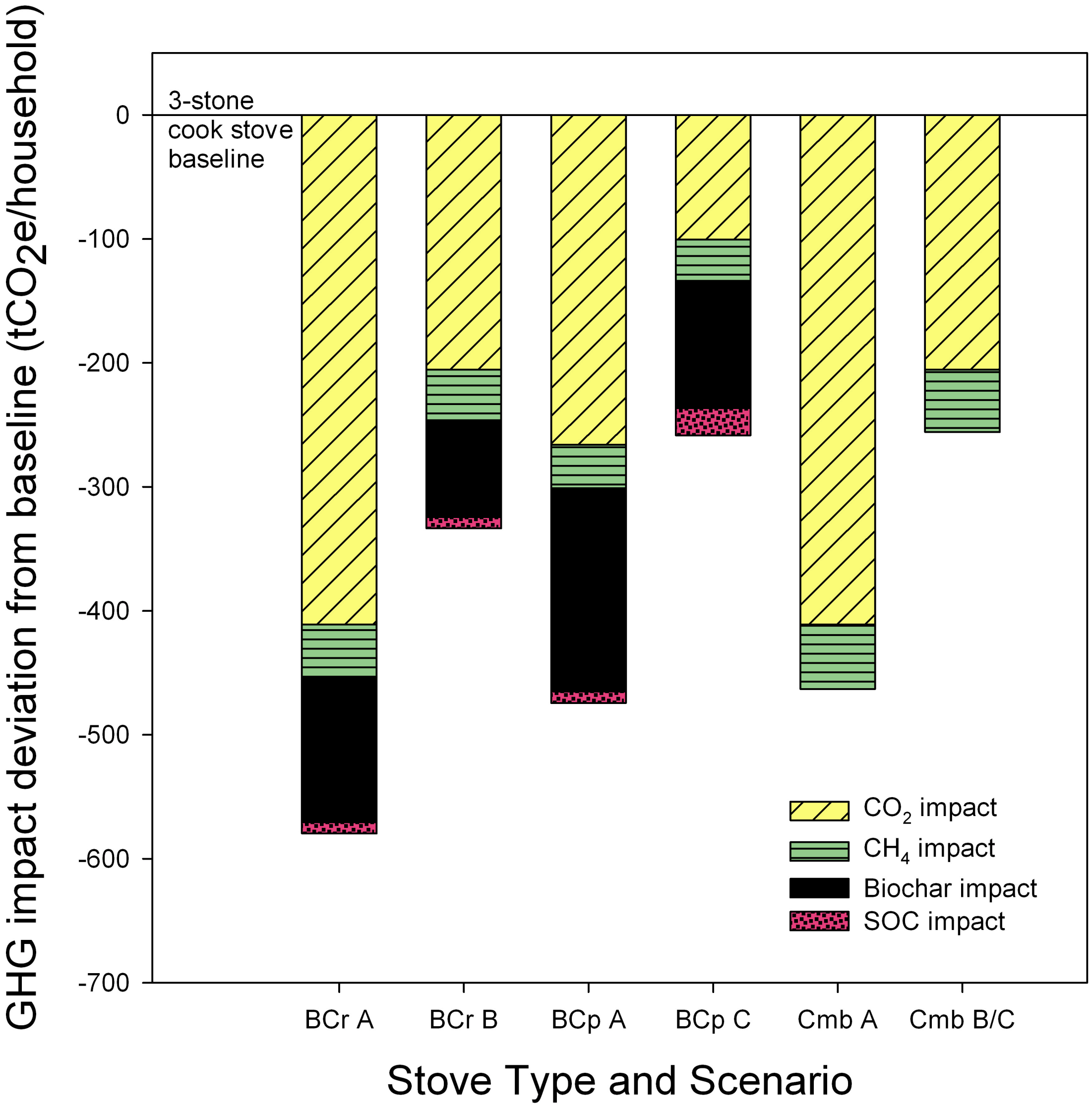


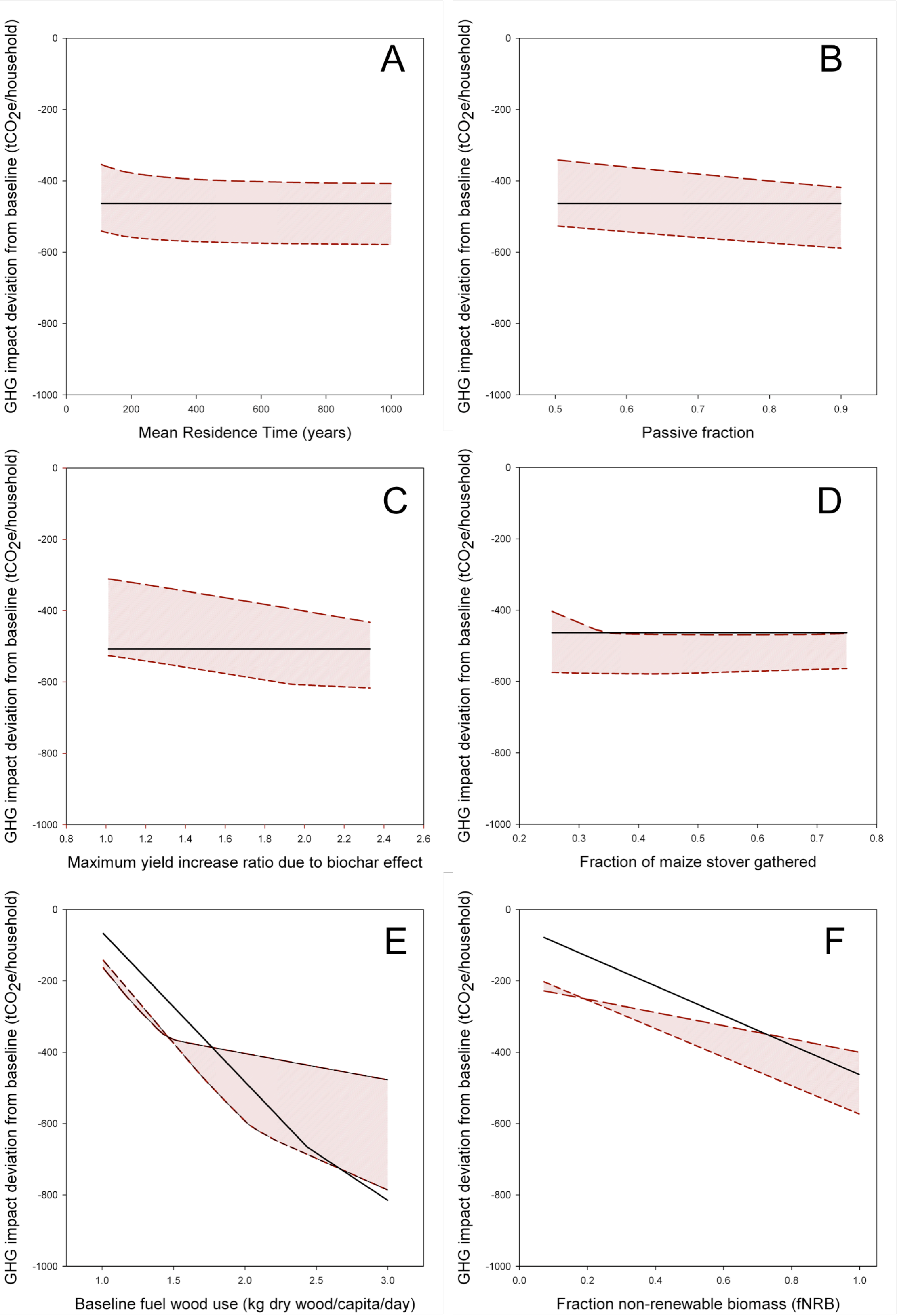
Figure 2.1. Simulated GHG impact deviation from baseline achieved after 100 years for the refined biochar-producing stove (BCr), the prototype biochar-producing stove (BCp), and the improved combustion stove (Cmb). The percentage of maize stover gathered was varied between 25-50%, fNRB of off-farm woodbetween 0.5-1, and MRT of the stable fraction of biochar between 100-1000 years. The scenarios with the maximum and minimum impact deviation from baseline are reported for each stove and are indicated by letters. A: 50% gathering, fNRB=1, MRT=1000; B: 50% gathering, fNRB=0.5, MRT=100; C: 25% gathering, fNRB=0.5, MRT=100.

cook stoves in Mexico, who reported that, over a 7-year period, the 95% confidence interval was 2.3-3.9 tCO_2e/household/year. Our results for the first seven years of model simulation are of the same order of magnitude as Johnson *et al*. [5], but are 12-23% less than the 100-year values for the pyrolytic cook stoves. This somewhat smaller estimated impact is largely because the effect of biochar application to crop yields is not at its maximum initially. Still, these rates of emissions reduction could allow stove projects to access C financing if the monitoring costs were similar to those discussed in Johnson *et al*. [5]. Monitoring costs may be similar for the improved combustion cook stove, but monitoring would be more complex if the emissions reductions due to biochar were counted as well, and thus, potentially more expensive [11]. However, if the values of biomass stabilization as biochar and changes in SOC stocks are ignored and only reductions in gaseous emissions were counted, this would reduce the annual creditable emission reductions by 16-36% for the refined biochar cook stove, and 29-57% for the prototype biochar cook stove, thus decreasing the economic viability of the project for biochar-producing cook stoves.

2.3.2 Sensitivity analysis

Increasing the MRT of the passive fraction of biochar (Figure 2.2A) increases GHG impact deviation from baseline by 18% between 100 and 400 years, but only by 4% between 400-1000 years. As highlighted in previous research [11, 38], determining the precise MRT of biochar beyond a few hundred years is not as critical within this timescale as determining the passive fraction (Figure 2.2B), which increases GHG impact deviation from baseline by 24% over the range explored here. Future research could focus on methods for establishing that MRT is above a certain threshold for a given passive fraction, in order to facilitate robust quantification and prediction of biochar stability.

Figure 2.2. Simulated sensitivity of calculated GHG impact deviation from 3-stone stove baseline after 100 years when key parameters are varied. The prototype pyrolysis stove is represented by the long dashed line, the refined pyrolysis stove by the short dashed line, and the improved combustion stove by the solid line. The shaded area highlights the range between the mean values of the two pyrolysis stoves. A – Mean residence time (MRT) (100-1000 years), B - Passive fraction (0.5-0.9), C – Maximum yield increase ratio due to BC effect (1.0-2.3), D – Fraction of maize stover gathered (0.25-0.75), E – Baseline fuel wood use (1.0-3.0 kg dry wood/capita/day), F – Fraction of non-renewable biomass from off-farm wood harvest (fNRB) (0.0-1.0). More negative values indicate greater GHG reductions. See SI for sensitivity analysis of initial farm age.


A
GHG impact deviation from baseline (tCO2e/household)
0
-200
-400
-600
-800
-1000
0
200
400
600
800
1000
Mean Residence Time (years)
B
GHG impact deviation from baseline (tCO2e/household)
0.5
0.6
0.7
0.8
0.9
Passive fraction
C
GHG impact deviation from baseline (tCO2e/household)
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
Maximum yield increase ratio due to biochar effect
D
GHG impact deviation from baseline (tCO2e/household)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Fraction of maize stover gathered
E
GHG impact deviation from baseline (tCO2e/household)
1.0
1.5
2.0
2.5
3.0
Baseline fuel wood use (kg dry wood/capita/day)
F
GHG impact deviation from baseline (tCO2e/household)
0.0
0.2
0.4
0.6
0.8
1.0
Fraction non-renewable biomass (fNRB)

The degree to which biochar enhances maize yields affects both SOC inputs from the crop and also the amount of available renewable biomass, which, in turn, affects biochar and direct stove emissions accounting (Figure 2.2C). Whether both these factors are critical depends on the stove's fuel requirements – the lower sensitivity in the refined pyrolysis stove beyond a ratio of about 1.9 indicates the point at which sufficient renewable biomass is provided. If, for example, biochar were not applied to the fields so the expected yield increases did not occur (ratio = 1.0), emissions reductions would be 28% smaller for the prototype pyrolysis stove and 16% smaller for the refined pyrolysis stove.

Although the net change to the GHG impact from SOC is small relative to the changes from gaseous emissions or biochar production, maintaining SOC is important for other reasons, such as soil structure, erosion control, biodiversity, and fertility [39]. The proportion of maize stover that is gathered (Figure 2.2D), is critical for determining SOC stocks, but also impacts the renewable biomass available as fuel for the stove, or the effective system-level fNRB. Thus, a range of dynamics is exhibited. As shown for the prototype pyrolysis stove, under conditions where there is insufficient renewable biomass to satisfy all the fuel needs of a household, increasing the fraction of maize stover gathered results in a greater reduction in GHG impact (up to around 35% of biomass being gathered). Beyond this point, gathering more biomass results in relatively small gains. The refined pyrolysis cook stove shows that for rates of gathering above 42% of maize stover, SOC reductions from gathering more stover are not offset sufficiently by yield increases from applying the biochar to the fields, thus reducing the net benefit. (SOC dynamics are discussed in greater detail in the SI.)

The baseline demand for wood fuel (Figure 2.2E) has a strong linear scaling effect on the GHG impact for all stoves, particularly the improved combustion stove. As baseline fuel use increases, the absolute reductions increase as well. The inflection points around 1.4 kg dry wood/capita/day for the prototype biochar cook stove, 2.0 kg dry wood/capita/day for the refined biochar cook stove, and 2.4 kg dry wood/capita/day for the improved combustion cook stove indicate the points beyond which the household must begin to access non-renewable off-farm wood biomass sources in order to meet their needs, decreasing the rate at which reductions increase with increasing baseline fuel use. Beyond this point, the steepness of the slope is influenced by stove's fuel demand – the more fuel the stove needs, the less sensitive it is to changes in baseline fuel use, as seen in the prototype stove. Higher fuel demand also means that a greater fraction of the stove's GHG impact reductions come from biochar production. Under highly renewable scenarios, the prototype stove is actually somewhat better than the refined stove, because its greater fuel use means it produces more biochar, which leads to increased SOC levels.

The fNRB of off-farm wood (Figure 2.2F), along with the baseline demand for wood fuel, has the greatest impact on emission reductions because it affects both which GHG emissions are counted and also whether biochar production is counted as C sequestration or as no net change in terrestrial C stocks, which have opposite responses to a changing fNRB. The less wood a stove uses, the steeper the slope of its fNRB sensitivity curve is, because the net effect of changing fNRB on the impact from the stove's total gaseous emissions is less similar between the improved stove and the 3-stone stove baseline. The greater the fraction of biochar that is produced, the lower the y-intercept of its fNRB sensitivity curve will be, because less of the total C fuel is emitted and more is sequestered as biochar, but it will not change the slope of the sensitivity curve. Over the range considered here, the refined pyrolytic stove has a similar degree of sensitivity to the combustion stove, but the less efficient prototype stove is ~55% less sensitive to changes in the fNRB of off-farm wood. The prototype pyrolysis and the combustion stoves produce equal emission reductions at an fNRB of off-farm wood of around 0.73, while the two biochar cook stove scenarios are equal at an fNRB of 0.2. It is also clear that in systems relying mostly on renewable biomass sources as fuel, using a biochar-producing stove that requires more fuel would actually result in a greater reduction in GHG impact than a highly fuel-efficient stove. However, we note that this is considering only the GHG impact, and may not reflect the optimal solution for addressing other air pollutants.

2.3.3 Policy analysis

The inclusion of non-Kyoto-regulated CO gas and particulate black C (Figure 2.3A) increases the net GHG impact reductions from the baseline scenario by 6.9% for the refined pyrolysis cook stove, 7.6% for the prototype biochar cook stove, and by 8.8% for the improved combustion cook stove. Their inclusion accentuates the importance of the gaseous emissions and those factors that affect the accounting of emissions, such as the fNRB. Even though the $CO:CO_2$ ratio is higher for the pyrolysis stoves than for the improved combustion cook stove (Table 2.S2), which would increase the effect of including non-Kyoto gases, gaseous emissions make up a greater fraction (100%) of the net reductions from baseline for the improved combustion stove, so including non-Kyoto gases increases the GHG impact reduction more for the improved combustion cook stove than for both pyrolysis cook stoves.

When biochar that was produced from unsustainably harvested woody biomass is counted as an effective instant emission, rather than a neutral change in C stocks (Figure 2.3B), the net GHG impact reduction from the baseline scenario decreases by 0.21% for the refined pyrolysis cook stove and by 4.3% for the prototype pyrolysis cook stove. Although there is no net change in terrestrial C stocks when biochar is produced from unsustainably harvested wood, as the system is defined here, there

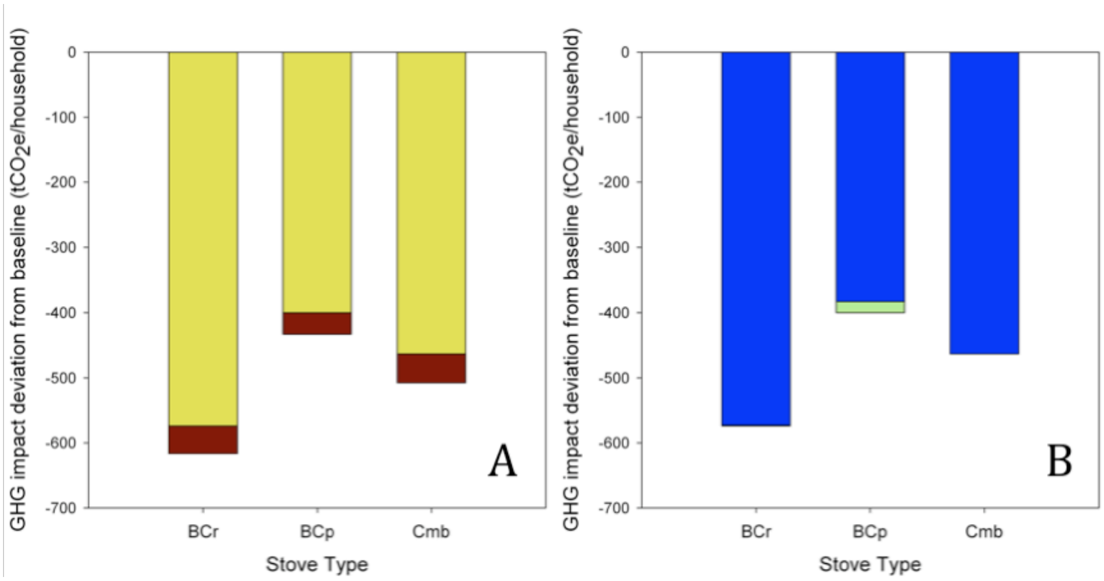


Figure 2.3. Simulated influence of policy choices on GHG impact deviation from baseline. A - Non-Kyoto gases are included (full bars) or excluded (shorter, yellow bars only) from the GHG accounting of the system. B – Biochar produced from unsustainably harvested wood is considered to be neutral as long as it remains stable (full bars) or is treated as a net loss of C to the atmosphere upon conversion (shorter, blue bars only). Results are shown for the refined biochar-producing cook stove (BCr), the prototype biochar-producing cook stove (BCp), and the improved combustion cook stove (Cmb).

could be other reasons that one would choose to value either C in the form of a living forest or C in the form of biochar for soil improvement over the other. An NGO focused on forest preservation might choose to value standing forests, whereas a farmer might not place the same value on intact forests as on forests cleared for agriculture, combined with biochar production for soil application that results in more productive soils. This decision might be made when applying C accounting to a biochar system in order to ensure that an incentive for deforestation is not inadvertently created. Although the biochar stove modelled here uses less wood than the baseline scenario's 3-stone stove, one can imagine a scenario where a stove that uses more wood in total but produces enough biochar could mask the effect of increased deforestation since biochar production is counted as no net change. Thus, we have not made a value judgment in this model, but draw attention to this choice, which would have to be made when designing accounting protocols. Because the impact of this policy choice on the net reductions is relatively low, even at maximum fNRB, it may be possible to err on the side of forest preservation by counting biochar production from unsustainably gathered biomass as an immediate emission.

2.3.4 Applications

The appropriate stove for a given area depends on what characteristics and impacts are most valued. Besides factors influential in adoption of stoves [3, 40], such as construction materials or ability to provide cooking heat appropriate for the region or household (*e.g*., two pots *vs*. one or a large flat cooking area *vs*. a flame), the major drivers for stove projects are related to improving respiratory health, decreasing forest degradation and harvesting efforts, mitigating climate change, and, in the case of biochar, on-farm biomass management for soil fertility and food security. This paper investigates only the mitigation of climate change in detail, and these other factors would have to be weighed in developing any stove project. Our modelling shows that even the prototype biochar stove is likely comparable to improved combustion cook stoves in terms of reducing GHG impact, but has the additional beneficial dynamics of biochar production and associated crop yield increases, which could have important effects on food security in developing regions such as the one considered in this study. While this aspect of biochar cook stoves would be considered an advantage for its users, it is an additional challenge for those accounting for its GHG reductions. Because biochar production makes up a significant component of these reductions, if pyrolytic stoves are to access carbon markets for financing stove projects, robust metrics for measuring and verifying the GHG impacts of biochar production must be developed [11]. By identifying fNRB and baseline fuel use as particularly influential parameters, relative to biochar stability, farm age, or crop residue gathering, this paper takes an important step toward doing just that. Future research might focus on better characterizing fNRB values or replacing it with direct measurement and analysis of C dynamics within the system, as SImpaCCT does for maize residues, and then targeting stoves based on biomass resource availability of specific systems.

2.4 Supporting information

More detail on model development and evaluation, further simulation results, and the model itself follow in the supporting information section.

SUPPORTING INFORMATION FOR CHAPTER TWO - CLIMATE CHANGE IMPACT OF A BIOCHAR COOK STOVE IN WESTERN KENYAN FARM HOUSEHOLDS: SYSTEM DYNAMICS MODEL ANALYSIS

2.S.1. Study system location

The modelled system is located in the western Kenyan highlands (Figure 2.S.1).

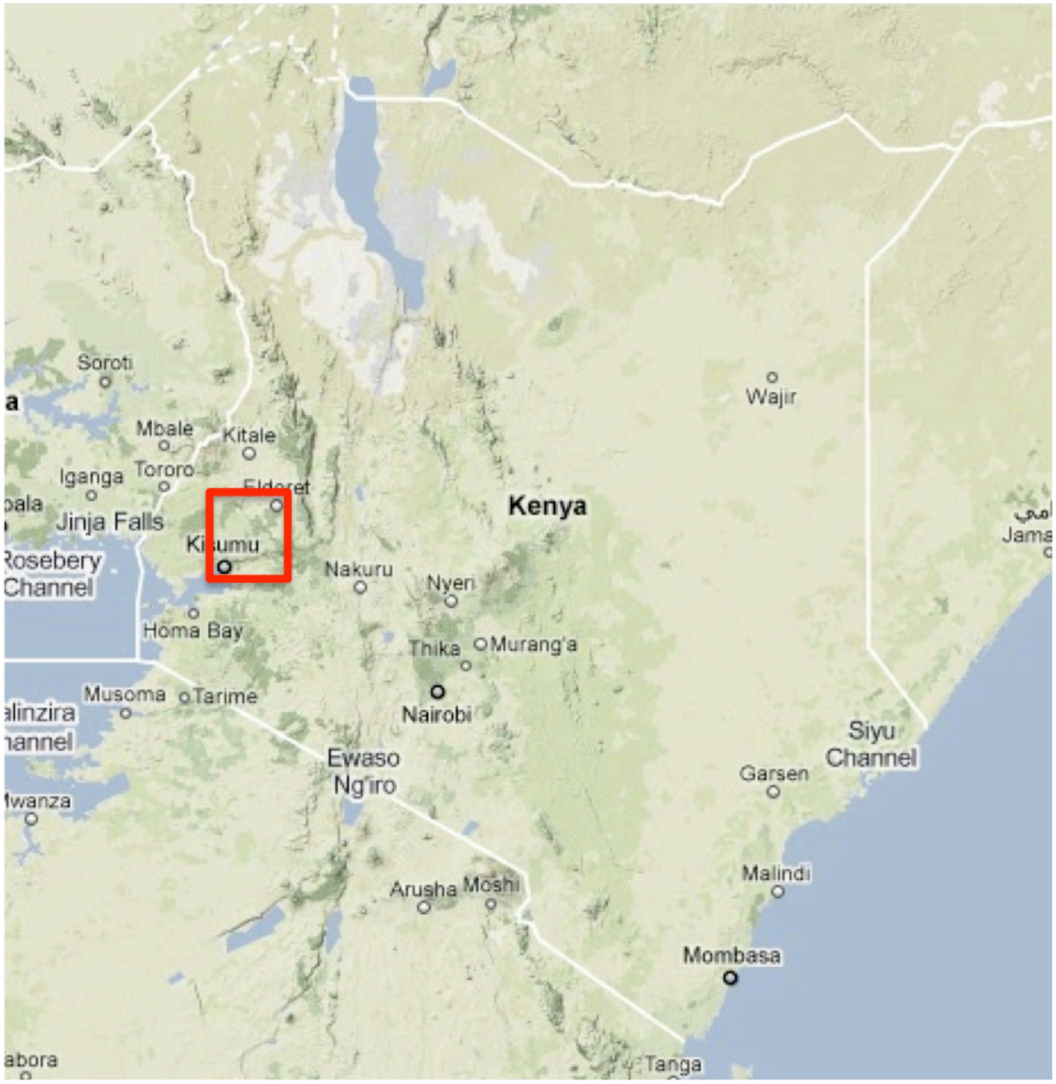


Figure 2.S1. Studied region in the western Kenyan highlands indicated in rectangle. Map from Google maps (maps.google.com).

2.S.2. Model module overview

The model consists of four interlinked modules (Figure 2.S.2).

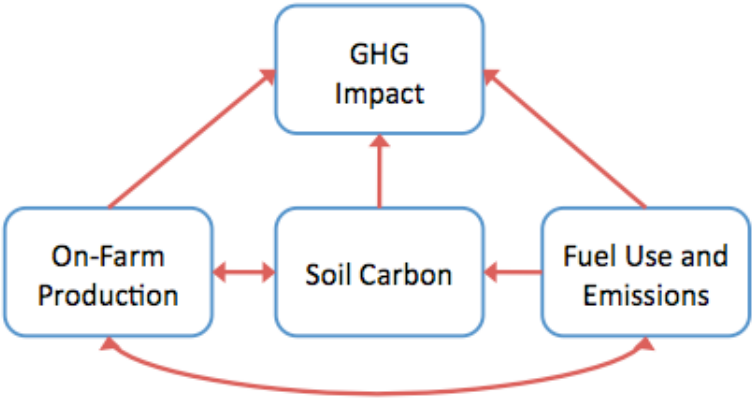


Figure 2.S2. Model modules and their interconnections

2.S.3. On-farm biomass production

An overview of the on-farm biomass production module is illustrated in Figure 2.S3.

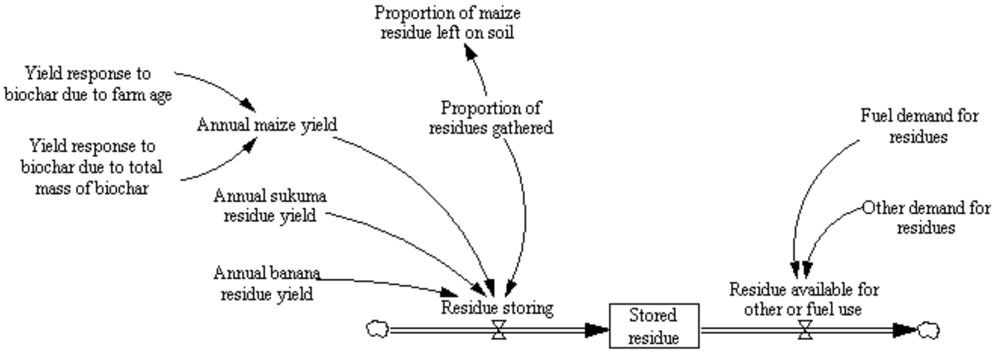


Figure 2.S3. Overview of on-farm biomass production module

The annual maize stover yield is calculated based on mean yields for short and long rains. Maize grain yields for the long-rains season (March-May) are based on the mean values from farm plots amended with only K and P (100kg/ha/year for each), from seasons 2004-2009 and decline with increasing time since farm conversion from forest (Figure 2.S4). Limited data are available (2004 only) for the short rain season (October and November), so the mean 2004 value across conversion years, 2.4 t dry grain/ha, is used [1]. Data from field surveys of 60 farmers indicated that around 25% of stover is currently used for other uses, such as lighting fires or feed for animals, while 75% is left on the field.

To predict cob yield, a linear equation relating the ratio of cob:grain mass yield per hectare to farm age was fitted for the cob and grain mass data collected, giving cob:grain ratio = 0.3613+0.002*[conversion year], or, if data from the year 2009, which was a bad drought year, are included, cob:grain ratio = 0.0057+0.3049*[conversion year]. Cobs are commonly used to light fires, and while they could feasibly be used as fuel in a pyrolytic stove, it is assumed that they would continue to be used for lighting fires, and thus are not included as an additional biomass source.

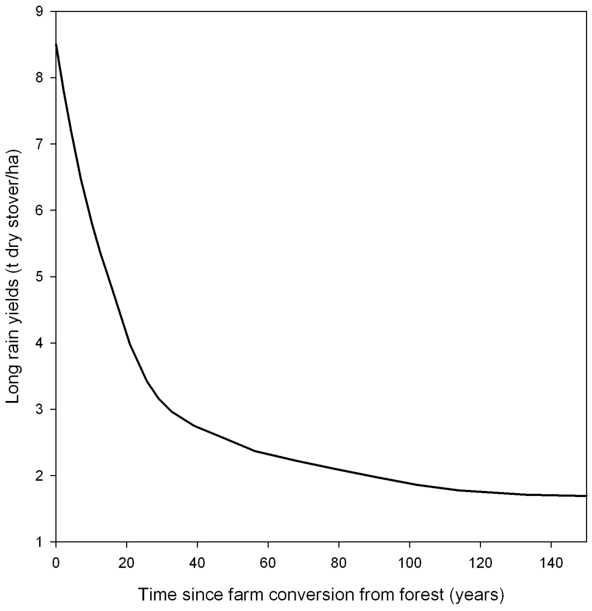


Figure 2.S4. Long rain maize stover yield over time, based on 2004-2009 chronosequence data

The magnitude of the crop's response to biochar application is based on the age of the farm and the total biochar that remains on the soil, as shown in Equation 1,

$$Y_{A,BC} = Y_B \cdot I_{\max} \cdot \left(E_{BCA\left(\frac{A_F}{A_{F\max}}\right)} \right) \cdot \left(E_{BCS\left(\frac{S_{BC}}{S_{BC\max}}\right)} \right) \qquad (1)$$

where YA,BC is crop yield in t dry grain/ha for a farm at a given age (*A*) and soil biochar content (*BC*), Y_B is the baseline yield in t/ha, I_{max} is the maximum increase factor (2.2, or 120%, based on the mean increase in yields observed at 18t C/ha biochar application from Kimetu [2], A_F is the age of the farm and $A_{F\max}$ is the age of a farm above which the maximum benefit is garnered (set at 100 years), S_{BC} is the stock of all biochar in the soil, S_{BCmax} is the stock of biochar above which the maximum benefit is realized (estimated at 25t/ha), E_{BCA} is the degree of effect from biochar due to age, a value between 0-1 which increases rapidly over between 0-15 years, after which it increases more slowly (Figure 2.S5), and E_{BCS} is the degree of effect from biochar due to the total stock of biochar in the soil, also a value between 0-1, which increases steadily as the mass of biochar increases (Figure 2.S6). The two *E* functions serve to determine the degree to which the possible percent yield increase is realized, so if either has a value of 0, there will be no effect, and if both have a value of 1, then the full impact on yields, I_{max}, will occur. This response is analogous to N and P fertilizer response curves for these farms [1] (although biochar would not be expected to use the same mechanisms as fertilizers to increase yields).

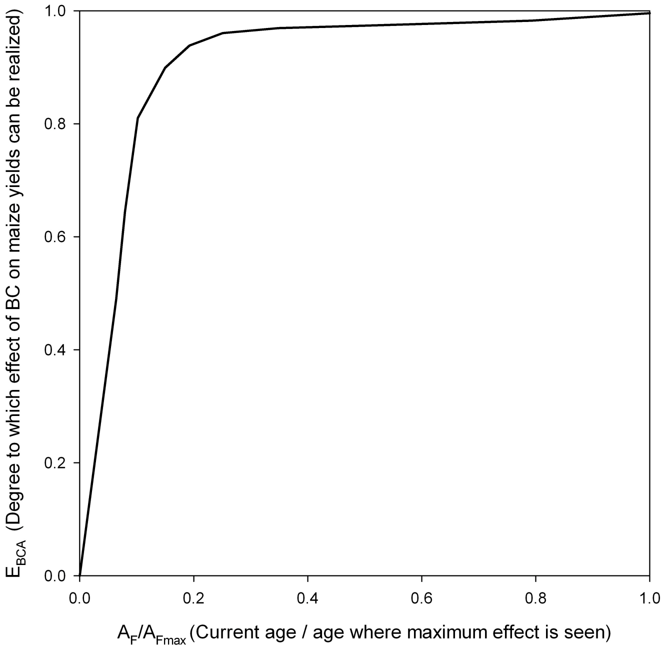


Figure 2.S5. Function indicating how farm age affects the degree to which the full effect of BC on maize yields is realized.

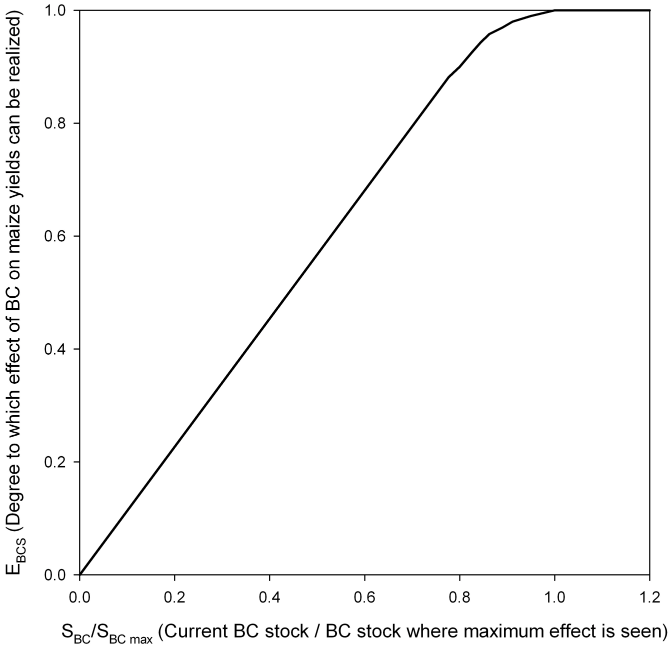


Figure 2.S6. Function indicating how biochar mass affects the degree to which the full effect of BC on maize yields is realized.

The studied farm chronosequence shows a decline in soil C, N, and fertility over time [2, 3], because of the specific practices applied to the fields and other land-use decisions. Thus, while farm age is used as a proxy for soil degradation over time in this model, the relationship of GHG reductions to age would not be directly transferrable to different systems, but the different results on soils of different fertility statuses would be more transferrable, as has been established for farm gradients [4].

Production of banana leaves and sukuma-wiki clippings represent residues that are currently unused on the farm, and were derived from on-farm biomass surveys conducted in 2008 by Dorisel Torres [5]. No consistent trend in yield was seen by conversion year, so the mean farm area devoted to each crop and the mean annual yield per hectare are used to calculate total available biomass (Table 2.S1). Production of on-farm wood represents the mean annual incremental (MAI) growth of on-farm trees, and was derived from on-farm biomass surveys conducted by Dorisel Torres in 2008 [5]. No consistent trend in MAI was seen by conversion year, so the mean farm area devoted to trees and the MAI per hectare across all farms are used to calculate total available biomass (Table S1).

Table 2.S1. On-farm biomass production

Biomass	**Area devoted to crop (ha)**	**Mean annual available yield (t C/ha)**
Banana	0.052	7.6
Sukuma-wiki	0.018	1.3
Wood	0.223	4.7

2.S.4. Fuel use and emissions

An overview of the fuel use and emissions module is illustrated in Figure 2.S7. Daily per-capita fuel use was calculated over 3-5 days in July 2009, using a Kitchen Performance Test (KPT) in 17 homes, 6 of which use 3-stone cook stoves, and 11 of

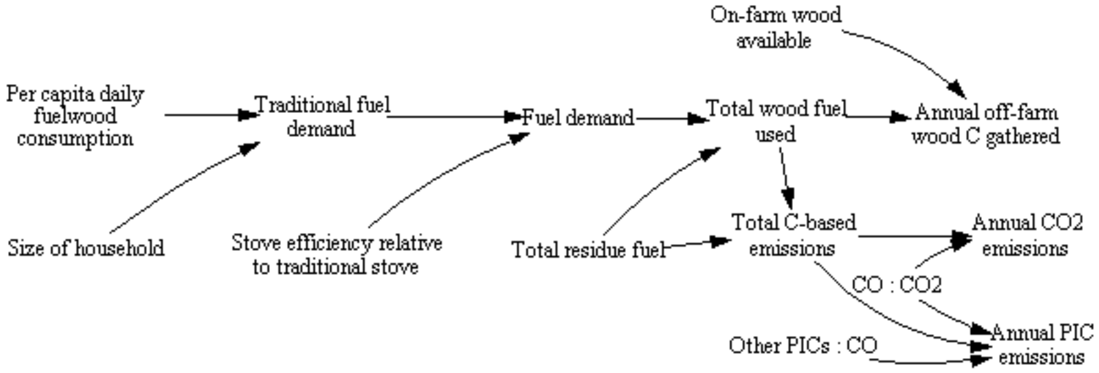


Figure 2.S7. Overview of fuel use and emissions module

which use modified mud cook stoves (locally referred to as Chepkube stoves). Fuel samples were taken at each weighing to determine moisture content, which was calculated as proportion of mass lost after heating to 70°C for over 48 hours, until constant mass was reached. The mean fuel use was 1.9±1.1 kg dry wood/capita/day for the 3-stone cook stove, and 1.4±0.7 kg dry wood/capita/day for the Chepkube stove. The value of 1.9 kg dry wood/capita/day was used in the model for the 3-stone cook stove baseline, but was subjected to sensitivity analyses that reflect the range of values observed. Relative stove fuel use was determined as described in the main manuscript and in Table 2.S2.

Table 2.S2. Modelled stove parameters

Stove type	**Fuel use (kg dry biomass / capita / day)**	**$CO:CO_2$ ratio by mass C**
3-Stone	1.95[1]	0.0513[4]
Rocket stove	0.72[2]	0.0155[5]
Pyrolysis stove	1.24 primary + 0.84 secondary (prototype); 1.022 primary + 0.70 secondary (refined)[3]	0.0252[6]

1. Measured using kitchen performance tests [6]; 2. Calculated using measured fuel use for the system and the fuel use ratio of 3-stone to rocket stove [7]; 3. Primary biomass is used to light the stove, while secondary biomass represents that which is pyrolysed. Values are from [5] and [7] 4. Mean value from high and low power WBTs from MacCarty *et al.* [7], Jetter and Kariher [8], and in-home cooking tests from Johnson *et al.* [9]; 5. Mean value of high and low-power WBTs of the rocket stoves in MacCarty *et al.* [7] and Jetter and Kariher [8]; 6. Gasification stove value in MacCarty *et al.* [7]

For calculating per-capita fuel use from the KPT, capita values are adjusted to a standardized unit: men over 14 years of age are weighted at 1.0, men over 59 at 0.8, women over 14 at 0.8, and children 14 and under at 0.5 [6].

For the pyrolysis stove, 59.5% of the C is retained in the biochar (mean measured for sawdust, maize cobs, and maize stover feedstocks from Torres [5]). Division of the remaining C between CO_2 and PICs is based on the relative ratios of these products. The $CO:CO_2$ ratio is a common metric for determining how efficient combustion of fuel is: a high ratio results from low-efficiency combustion with high PIC production (Table 2.S2). This ratio was calculated for a range of different stoves. Here, we use the mean value from high and low power WBTs [7, 8], and in-home cooking tests [9] for the 3-stone stove. Whether stoves are used at higher or lower power is determined by home-specific cooking activities, and the balance can be important in determining $CO:CO_2$ ratios, which, in turn, will influence stove GHG production, as illustrated by Johnson *et al*. [9]. The value used for the pyrolysis stove is based on the gasification stove measured in [7] and is in the mid-range of values calculated for improved cook stoves that do not use charcoal as fuel as measured by [8]. The $CO:CO_2$ ratio used for the rocket cook stove is taken from the mean value of high and low-power WBTs of the rocket stoves in [7] and [8]. We model the emissions of non-CO PICs as being proportional to CO emissions, based on mass ratios from [7, 9, 10], and [11] for CH_4 (0.063) and from [9] and [12] for EC (0.00011) and OC (0.042). Using these ratios, we divide the total C lost from the fuel during combustion among the four end products using eq. 2 to determine the mass of CO_2 released and the ratios above to determine the mass of the other C-based compounds released,

$$\mathrm{CO}_2 = \frac{C_E}{X_{CO_2} + (CO:CO_2)\cdot X_{CO} + (\mathrm{CH}_4:\mathrm{CO})\cdot X_{CH4} + (\mathrm{EC}:\mathrm{CO})\cdot X_{EC} + (\mathrm{OC}:\mathrm{CO})\cdot X_{OC}} \quad (2)$$

where X_Y is the molar mass ratio of carbon to compound Y and C_E represents the total mass of C emitted from the stove.

2.S.5. Soil carbon module

An overview of the soil carbon module is illustrated in Figure 2.S8. The soil C module was parameterized by fitting turnover time parameters for C pools so that with the measured maize stover inputs of farms of different ages providing the residue input, modelled SOC pool sizes corresponded to the measured soil C stocks, under the designed model structure (Table 2.S3).

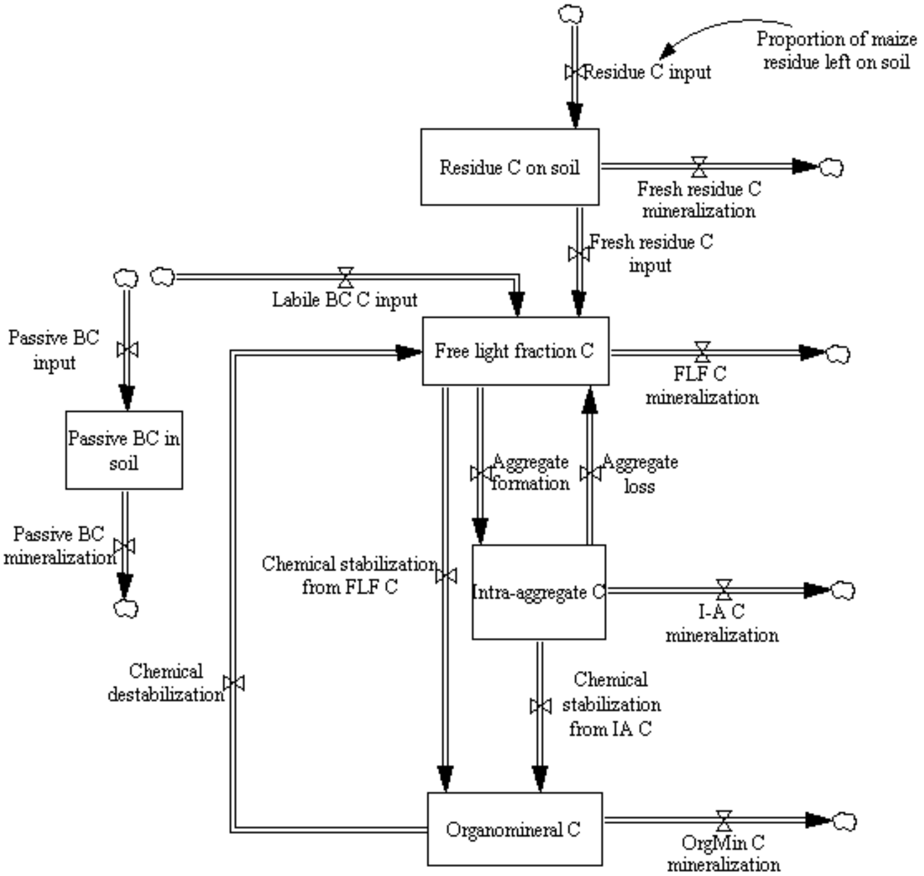


Figure 2.S8. Overview of soil carbon module

Table 2.S3. Soil carbon parameters after calibration

Pool	**Initial C stock when $A_{initial}$=1 (tC/ha)**	**Turnover time (years)**	**Fraction mineralized (%)**
Residue C	labile – 2.25 recalcitrant - 0.75	labile - 1 recalcitrant - 10	45
Free light C	15.85	1.75	45
Intra-aggregate C	6.525	1.83	55
Organomineral C	27.58	57.67	55

This resulted in simulation outcomes that compare well with experimental data, as shown in Figure 2.S9.

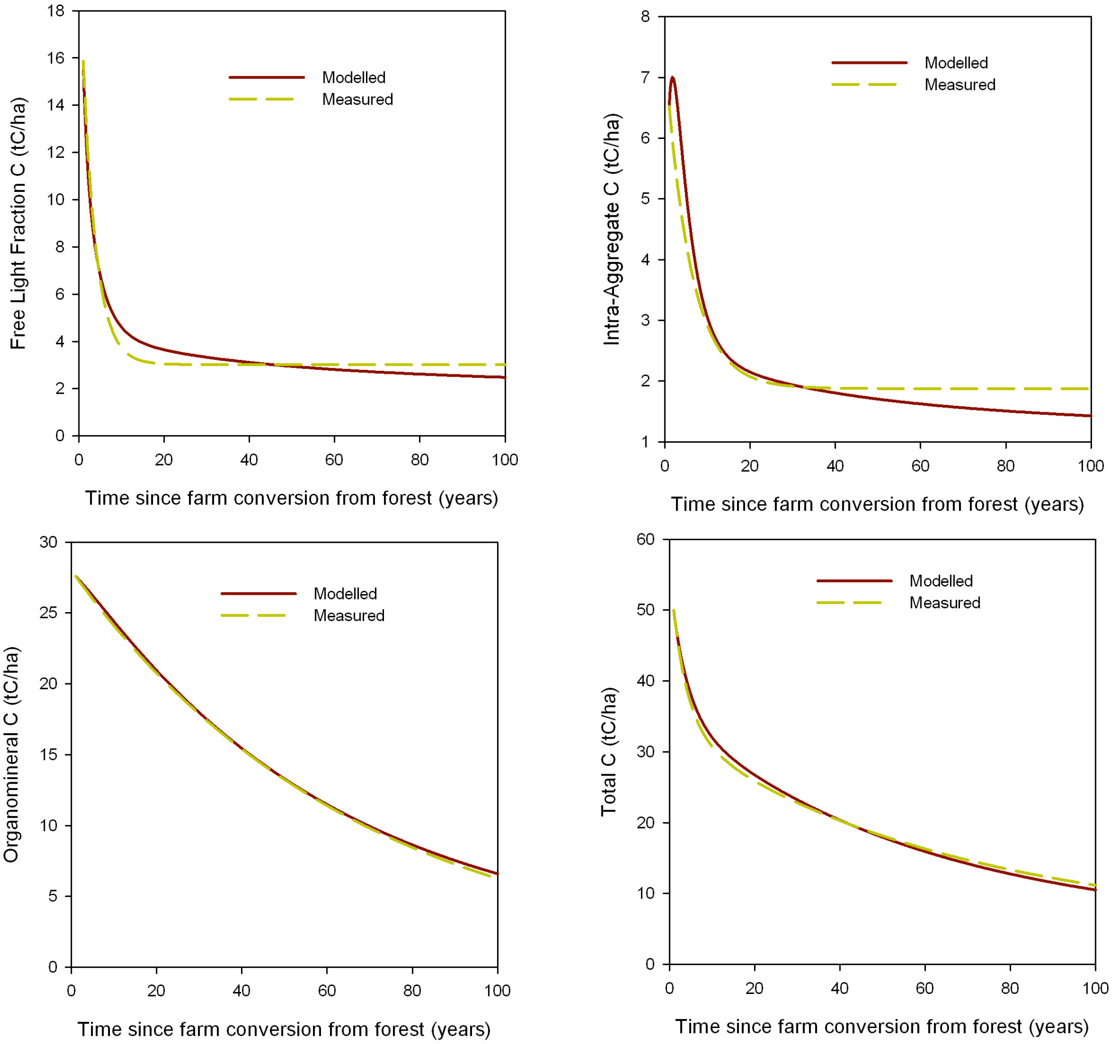


Figure 2.S9. Measured and modelled SOC pools after model parameterization

2.S.6. GHG impact

Characteristics of GHGs are listed in Table 2.S4.

Table 2.S4. GHG characteristics

Gas	GWP	rGWP	Kyoto Status
CO_2	1[a]	0	Included
CH_4	25[a]	22	Included
CO	1.9[a]	0.3	Not included
EC	597[b]	593	Not included
OC	0, but likely negative[c]	0, but likely negative	Not included

a. [13] b. [14-16] c. [17]

In general, any decrease in gaseous stove emissions produces a decrease in net GHG impact, *W*, while any increase in terrestrial C storage results in a decrease in *W*. The net change, ΔW_i, for a given stove, *i*, is calculated as shown (eq. 3),

$$\Delta W_i = (Wa_i - Wa_{3-stone}) - (Wt_i - Wt_{3-stone}) \quad (3)$$

where Wa_i represents net atmospheric GHG impact for a given stove, *i* and Wt_i represents net terrestrial GHG impact for a given stove, *i*. *Wt* and *Wa* are calculated differently for each biomass type, depending on whether all its C flows are included within the model boundary, as with maize stover (*m*), or whether its C flows are modelled, in part, indirectly and it is either non-renewable (*n*) or renewable (*r*), as these terms are defined in the paper.

We calculate the net GHG impact of released gases in terms of CO_2e, Wa_i for a given stove, *i* (eq. 4)

$$Wa_i = \sum_k \left(\left[G_{imk} + G_{ink} \right] \cdot GWP_k \right) + \sum_k \left(G_{irk} \cdot rGWP_k \right) + WaBC_{in} \quad (4)$$

where G_{imk}, G_{ink}, and G_{irk} represent the net gaseous emissions of GHG k, from either maize, non-renewable, or renewable fuel sources, respectively; GWP_k and rGWP_k are the GWP and renewable GWP, respectively, of GHG k; and $WaBC_{in}$ represents the CO_2 released from the mineralization of biochar produced from non-renewable biomass source n.

We calculate the net GHG impact of terrestrial C storage in terms of CO_2e, Wt_i, for a given stove, i (eq. 5)

$$Wt_i = (SOC_{im} + Cr_{im} + BC_{im} + BC_{ir}) \cdot M_{CO_2} \cdot GWP_{CO_2} \quad (5)$$

where SOC_{jm} is the total mass of SOC in the soil from maize stover; $\mathrm{Cr}_{\mathrm{im}}$ is C in gathered and stored maize stover; BC_{jm} and BC_{jr} are the total mass of C in biochar in the soil that was created from maize stover and renewable biomass, respectively; M_{CO2} is the molar mass ratio of CO_2 to C; $\mathrm{GWP}_{\mathrm{CO2}}$ is the GWP of CO_2. Equations 4 and 5 are used to solve eq. 3 for each different stove, i.

Recall that mineralization of BC produced from non-renewable sources is considered to be a net release of C to the atmosphere and that C stored in BC produced from renewable sources is considered to be a net withdrawal from the atmosphere, as elaborated on in the paper. We note that by excluding BC_{in}, we are assigning it an effective value of 0 – that is, as discussed in the paper, biochar produced from non-renewable biomass sources does not provide any net C storage. However, one could take the non-renewable or unsustainable scenario a step further and account for the loss of root, leaf, and soil C that are associated with the loss of wood during deforestation, which would require that we assign a negative value to BC_{in}. We have not taken this approach, recognizing that the fNRB is an abstraction to begin with and noting that an ideal solution would be to measure and model forest dynamics directly.

As well, we note that these equations for terrestrial carbon sequestration are based on the assumption that C mineralized from SOC, BC, or crop residue decomposition would be released in the form of CO_2. Accounting for the possibility that some of the C is likely lost as CH_4 would increase the GHG storage value of any C remaining in these terrestrial pools, so not including loss as CH_4 results in a conservative estimation of GHG impact of the improved cook stoves.

2.S.7. Model evaluation

2.4.7.1 Model evaluation overview

This model was evaluated by examining its behavior, structure, and assumptions, asking, “Is this model useful and sufficient for addressing the research question?” The model is not accepted outright as true or rejected as false, but, rather, given a series of tests to better understand its strengths and limitations and how it might be improved or expanded. In addition to the sensitivity analysis discussed in the manuscript, there were a number of tests applied that are commonly used to evaluate system dynamics models [18].

2.4.7.2 Integration error

In dynamic models that use numerical integration, the calculation interval (time step) chosen can have a significant influence on model results. If the time step is too large, the model may generate spurious oscillations. A small time step value, although it avoids the generation of spurious behaviours, may markedly increase the calculations (and time) required for a simulation. To determine a reasonable time step value, we used the test proposed by Sterman [18], which halved the value of the time step and evaluated changes in model behaviour. In this case, we decreased the time step from 0.0156 months to 0.0078 months, and observed no major differences in the value or behaviour for all variables.

2.4.7.3 Boundary adequacy

Tests of boundary adequacy were used to examine the impacts of assumptions about which variables are endogenous, exogenous or excluded from the model structure. The most notable boundary issues are that the effects of wood gathering on forest C stocks in both vegetation and soil are not modelled explicitly, and are instead accounted for by using the extreme case assumptions discussed in the manuscript. As indicated by the high sensitivity of the net GHG impact difference from baseline to fNRB, if we had the data to directly model the forest accurately, this could substantially improve the ability of the model to predict the effects of changes in wood-gathering behaviour. This could be challenging, particularly due to the complex and heterogeneous nature of the natural forest system as well as the social and economic factors that drive wood-gathering behaviour over time and industrial influences (such as the impact of harvesting wood for large-scale charcoal fuel production). The fNRB approach is common [7, 19-21] and likely a good approximation, but it would be informative and beneficial to include forest dynamics within the system boundary, were the data available.

2.4.7.4 Behavioural reproduction

This test was used to determine whether the model can generate expected behaviour endogenously, and whether the model's behaviour corresponds to the real-world system. As shown earlier in the SI, the behaviour of the SOC passes this test. However, we note that the modelled decline in maize stover yields is not endogenous to the model. This is acceptable, because the model is not a crop growth model, *per se*, although it uses crop growth as an input. If this model were transferred to other systems, trends in crop yields (and their response to biochar application) would have to be assessed separately.

2.4.7.5 Structure assessment

This test was used to determine whether the model conforms to basic physical laws and assumptions of human behaviour. In terms of physical laws, the model appears to be robust – for example, in varying many different parameters, no physical stocks can be made negative. In terms of human behaviour, the model is currently limited – *i.e.*, the decision-making processes of the actors in the model are either built into the structure (such as the decision to use fuel from sustainable sources first) or not included (family size remains constant and planted crops do not change over time). However, the model could be expanded to allow for alternative assumptions about socioeconomic decision-making.

2.4.7.6 Dimensional consistency

We ensured that the dimensions of all stocks, flows, and other parameters are consistent with reality and with each other. A units analysis using the Vensim software reveals no errors in units, but this alone is not sufficient to determine dimensional consistency – by examining each variable and asking the question, "Are these the units we would normally ascribe to this item, and do they make common sense?" we arrived at the conclusion that the model is dimensionally consistent.

2.4.7.7 Parameter assessment

This test evaluated model parameter values by asking whether they have real-world counterparts, and if they are consistent with extant knowledge about the system. Most parameters in this model are based on published or unpublished data. In general, any limitations are documented in the model. The use of a C basis for measuring fuel consumption is not completely appropriate because actors in the model would not know the C content of a given fuel, or the total C they have stored in residues, and in this model, decisions are made based on this knowledge. However, it is a reasonable assumption, because these decisions are likely to be made on an estimated mass basis, which would be directly proportional to total C content.

2.4.7.8 Extreme conditions

We examined how the model responds when certain parameter values are at minima or maxima. We varied a variety of parameters, but found no critically aberrant behaviour. Its weakest point is in the human system – for example, the household size remains constant, even if crop yield declines or no wood is available, while we would expect that social changes would take place under food and fuel stress. Adding a human component to the model would be relevant, but is not critical for the questions of current interest.

2.S.8 Further soil carbon results

By drawing a wide system boundary that includes SOC on the maize fields, we see the impact of diverting crop residues from the fields to stove uses. The total SOC losses predicted in this model under 3-stone stove conditions for a newly converted farm are around 40tC/ha over 100 years, which is consistent with global SOC loss rates in agricultural soils [22]. The production of biochar and its addition to soils increases the amount of non-biochar soil carbon because it increases crop yields, thus enhancing net stover return to the soil (Figure 2.S10). As discussed in the main manuscript, increasing the gathering of stover could help provide a renewable source of biomass fuel, which could replace other biomass fuel sources. As well as being a climate change-related choice, the amount of stover to gather for fuel use is also an economic and agronomic choice, as increased use of corn stover for fuel could divert it from other uses, such as animal feed, or from the important role it plays protecting the soil [23].

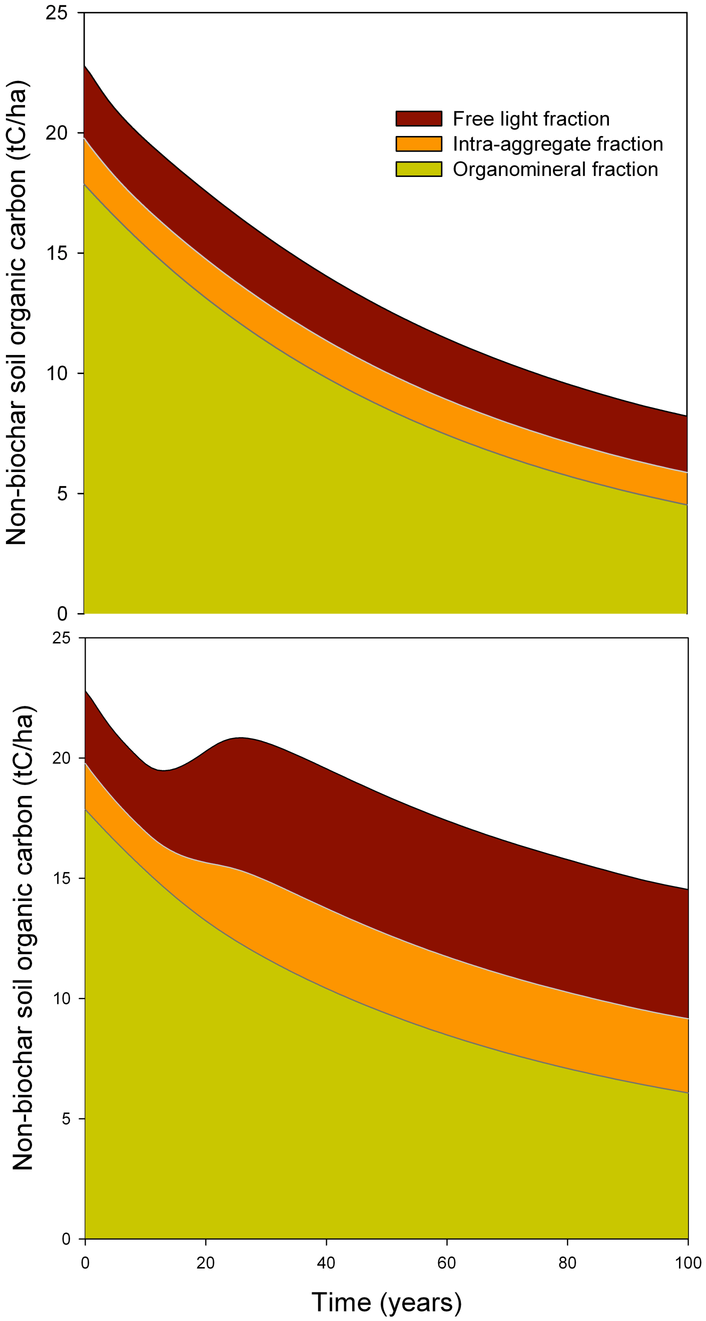


Figure 2.S10. Simulated non-biochar soil organic carbon stocks over 100 years under a 3-stone cook stove (top) and the prototype biochar-producing cook stove (bottom). Model settings are those used as default in the main manuscript – i.e., a 30-year old farm, which has already experienced soil carbon depletion.

If residue gathering were increased from 25% to 50%, this would initially deplete non-biochar SOC stocks, but as applied biochar increases crop yields, stover inputs increase to make up for this deficit (Figure 2.S11). Under the baseline model scenario described in the paper, the losses of soil C due to increased harvesting are not fully offset by increased crop growth until 20-25 years after the stove is introduced. This highlights the importance of the temporal dynamics that system dynamics modelling can allow us to appreciate.

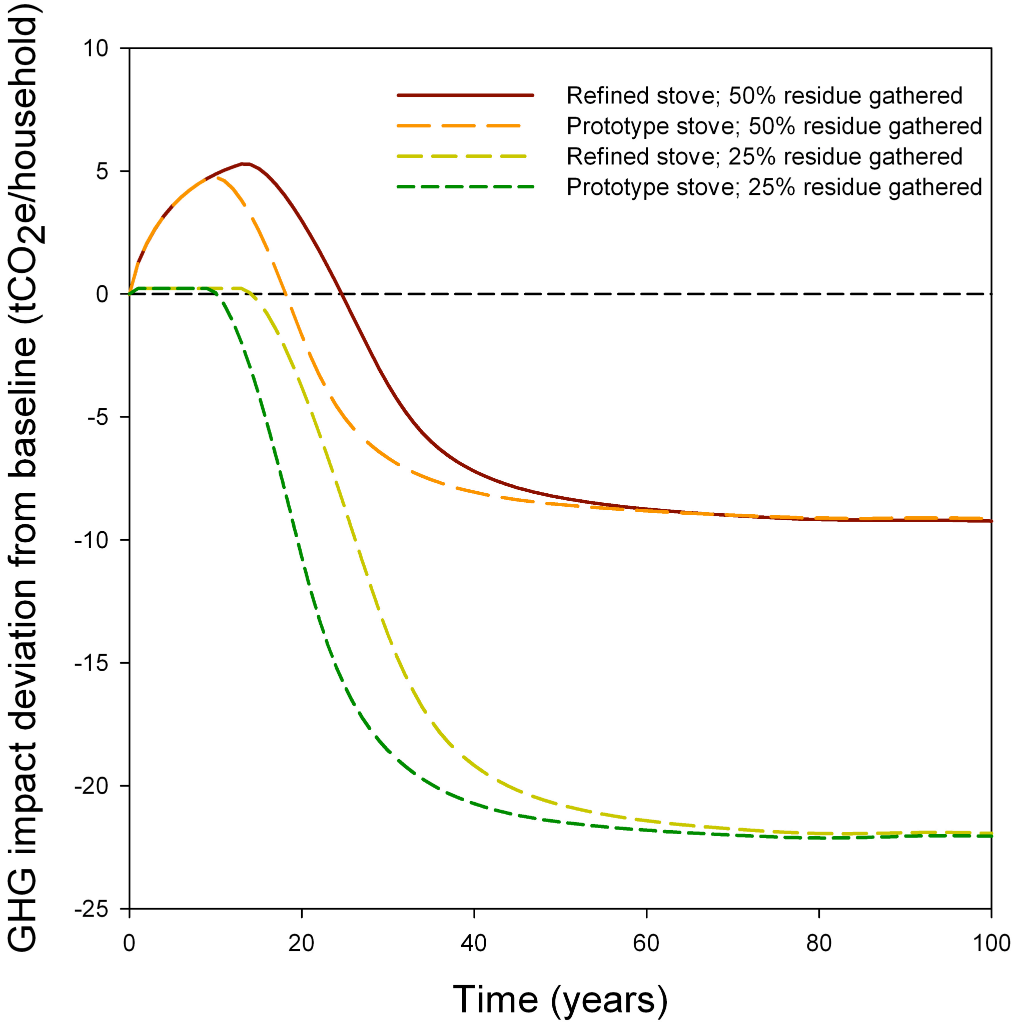


Figure 2.S11. Simulated non-biochar soil carbon GHG impact deviation from baseline for biochar producing stoves under 25% and 50% residue-gathering regimes over time.

2.S.9 Further sensitivity analysis results

Sensitivity analysis for the effect of initial farm age was conducted under the same conditions as for the parameters described in the paper. Varying time since farm conversion from forest or soil fertility status has a relatively small effect on the GHG impact (Figure 2.S12). Thus, having a wide range of farm ages or soil fertility statuses in a given project may not be a significant issue. Although the farm age is primarily important for determining SOC stocks and the effect of BC application on maize growth, changes in initial SOC stocks are not very influential for the net GHG impact (Figure 2.1).

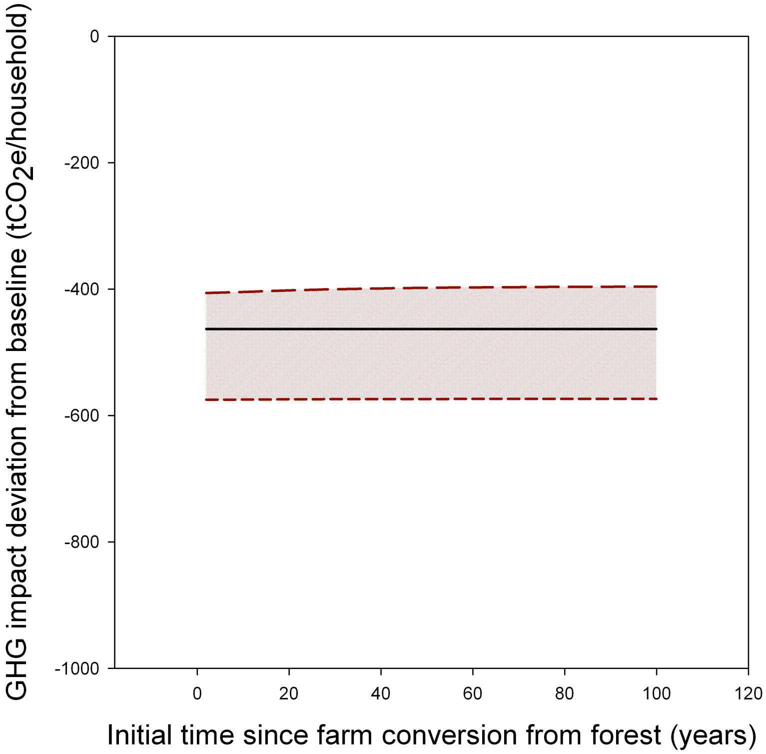


Figure 2.S12. Simulated sensitivity of calculated GHG impact deviation from 3-stone stove baseline after 100 years when initial farm age is varied between 1 year and 100 years. The prototype pyrolysis stove is represented by the long dashed line, the refined pyrolysis stove by the short dashed line, and the improved combustion stove by the solid line. The shaded area highlights the range between the mean values of the two pyrolysis stoves. More negative values indicate greater GHG reductions.

2.S.10 References for supporting information for Chapter Two

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CHAPTER 3

BIOCHAR PROJECTS FOR MITIGATING CLIMATE CHANGE: AN INVESTIGATION OF CRITICAL METHODOLOGY ISSUES FOR CARBON ACCOUNTING[3]

Abstract

Biochar is a potential tool in our fight against climate change, driven by its high carbon stability and supported by its roles in bioenergy and soil fertility. We consider methodology aspects of biochar systems used for carbon management and investigate the criteria for establishing additionality, baselines, permanence, leakage, system drivers, measurement, verification, economics, and development for successful stand-alone projects and carbon offsets. We find that explicitly designing a biochar system around "true wastes" as feedstocks combined with safe system drivers could minimize unwanted land-use impacts and leakage. Applying baselines of biomass decomposition rather than total soil carbon is effective and supports a longer crediting period than is currently standard. With biochar production introduced into bioenergy systems, under a renewable biomass scenario, the change in emissions increases with higher fuel use, rather than decreasing. Biochars may have mean residence times of over 1000 years, but be accounted for more effectively using a recalcitrant and a labile fraction.

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3.1 Introduction

Interest in biochar as a tool to fight climate change has led to the exploration of how biochar projects might use the stabilization of biomass carbon (C) into C-rich biochar while capturing energy for mitigating climate change [1-6]. While greatly reducing our use of fossil fuels must be our primary focus, “safe levels” of CO_2 in the atmosphere are thought by some to be lower than even present-day values, requiring significant draw-down of CO_2, in which biochar might play a part [7]. In order for biochar systems for climate change mitigation to be developed, we must devise a methodology to evaluate how much carbon a biochar project could sequester over an appropriate timescale (permanence) and determine best practices for application to systems such as the Kyoto Protocol’s Clean Development Mechanism (CDM) [8]. This paper takes a step toward this task, by reviewing some key methodological issues for implementation of biochar in climate change mitigating projects, considering additionality and baseline establishment, permanence, leakage, measurement and verification, economics and development issues.

3.2 Biochar projects and carbon markets

Biochar is a carbon-rich organic material that results from the heating of biomass in the absence, or under a limited supply, of oxygen. This process is called “pyrolysis”, and has been used to produce charcoal as a source of fuel for millennia [9, 10]. Recently, interest has grown in understanding the potential of this process to improve soil health by adding biochar as an amendment to soil, to manage agricultural and forestry wastes, to generate energy, and to store C [11]. Biochar is included in the spectrum of black carbon materials – the name “biochar” is used here to distinguish it from charcoal created for fuel, and to denote its particular application in carbon-sequestering and emission-reducing projects as a soil amendment. A very wide range of methods can be used to produce biochar, from systems such as the industrial biochar production system, to biomass-fuelled cook stoves that produce biochar as well as heat for cooking [12].

Carbon offsets are based on the principle of efficiency in addressing climate change. In general, emissions are to be reduced at their source. However, for efficiency and flexibility reasons, agents operating in a carbon-constrained environment are usually allowed to acquire carbon offsets (or allowances). These assets are bought when marginal abatement costs at the emissions source exceed the market price for an offset (or allowance). Compliance offset markets exist as a part of carbon regulation schemes, where offset mechanisms allow parties with emissions reduction targets (caps) to meet a portion of their targets by purchasing or trading emission credits that are generated through the implementation of greenhouse gas (GHG)-reducing projects outside the regulated regime. The most well-known offset mechanism is the Clean Development Mechanism (CDM) under the Kyoto Protocol [13]. At the same time, a significant “voluntary carbon market” has developed alongside the compliance market, driven by businesses interested in corporate responsibility or by individuals who compensate for their personal footprint of GHGs, for example, when taking an airplane flight.

Since offsets basically increase the overall volume of emissions allowed to be emitted system-wide if strict additionality is not ensured, their availability can potentially provide a misleading sense of security and simply postpone the fundamental changes necessary to effectively mitigate climate change. We do not make a case for or against offsets here [14-17], and emphasize that the need to stop our reliance on fossil fuels is of the foremost importance in the climate change fight, before offsets and other solutions. There is no reason that biochar projects must be applied within an offsetting system – they could be applied to mitigate climate change directly – but many of the basic principles of offsetting must be included when evaluating whether a biochar project should be recommended.

Within a biochar project, emissions reductions (ERs) could come from changing fresh organic matter to a much more stable form of carbon through the production of biochar, from increasing soil carbon stocks upon biochar application, possible reductions in soil emissions of GHGs, enhanced C storage in growing crops, and decreases in fertilizer and other energy-intensive agricultural inputs (Figure 3.1, Source of Reductions) [1, 4, 18]. As well, impacts directly related to avoided emissions associated with the substitution of fossil fuel by bio-energy created during the pyrolysis process could be counted. In the case of a cook stove system, for example, reductions would come from higher stove efficiencies, resulting in lower total biomass gathering for fuel use, and cleaner cooking heat production, resulting in lower GHG emissions per unit of fuel used. An industrial biochar system, on the other hand, could also derive credits from replacing fossil fuels with a renewable biomass fuel source.

To date, no biochar-specific methodologies have been approved. The biggest step needed before biochar projects can generate carbon assets, which could be used as offsets, is the development of methodologies to account for the specific impacts of biochar's application to soils and sequestration, as this is where biochar projects are unique.

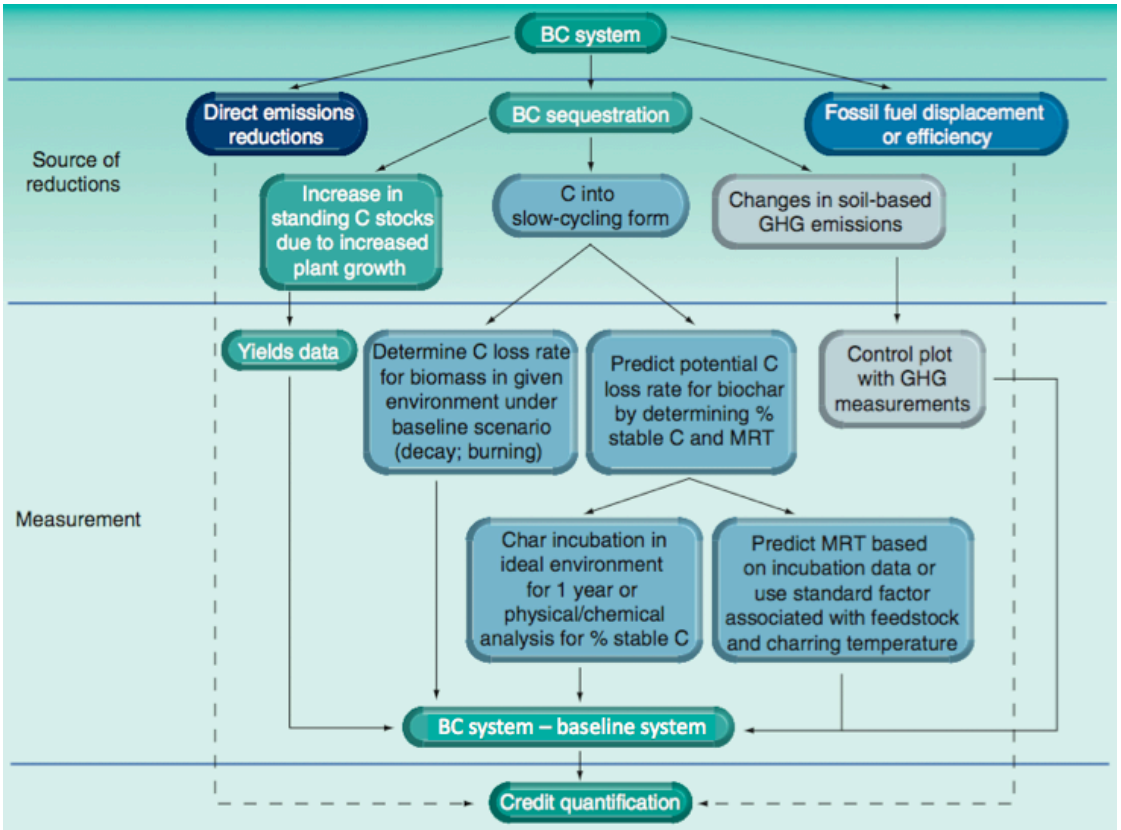


Figure 3.1. Potential measurement scheme for biochar-based carbon credits

3.3 Principles of carbon accounting for biochar projects

3.3.1 Introduction to carbon accounting

There are a number of factors that are necessary to successfully create a carbon asset in climate change mitigation projects [19-21]. We will not provide a review of all of these here, but, rather, investigate key aspects of a selection of those with particular implications for biochar projects: additionality and baseline establishment, permanence, leakage, measurement and verification, economics and development issues, with a view to establish a framework for a methodology used to produce carbon assets from biochar projects. We focus on the aspects of carbon management specific to carbon in biochar, because although many biochar-producing systems would reduce GHGs through displacement of fossil fuels or energy efficiency, methodologies for making such measurements are better established than those for biochar, which are largely nonexistent. There are many other non-GHG potential impacts of biochar's application to soils and variability in these impacts due to different feedstocks and production conditions [22-25], which would need to be considered and standardized for any successful biochar project, but these are not the focus of this paper.

3.3.2 Additionality and baseline establishment

If an offset project is being used as justification for emissions to continue elsewhere, we must be convinced that the project differs from the business-as-usual scenario – for example, legal regulations would not have required the changes during the lifetime of the project anyway, *i.e.*, the project is "additional". The CDM's "additionality tool" is the most prominent method of establishing the additionality of a project [26]. So long as there are financial or other barriers to its implementation and it is not yet common practice, a project may be deemed additional [24]. With regards to additionality, biochar projects may have an advantage. Because they are currently uncommon technologies and not widespread methods of biomass management or energy production, one may argue that they would not have occurred without carbon sequestration as a driver. However, because there may be numerous co-benefits [22, 23, 27, 28], if these are deemed sufficient to push the development of biochar systems without carbon finance, then additionality would need to be re-addressed.

Emissions reductions are established by predicting what would have happened if the project were not implemented (the baseline scenario) and then comparing this to what does ensue (*i.e.*, the "with-project scenario"). The establishment of baselines can be challenging, due to the counterfactual reasoning involved and the challenges in predicting natural systems or economic and technological development over many years. This challenge is one of the primary reasons that offsetting projects have a limited duration, called a ‘crediting period’, during which they can deliver credits, sometimes with the option for review and renewal after the first crediting period. Under the CDM, forestry projects have longer durations, due to the longer timeline needed for effects of terrestrial sequestration to become apparent and to incentivize longer-term forest rotation periods [29].

Biochar fits into this space in a complex way – most biochar projects would include standard energy-based emission reductions. Shorter crediting periods related to energy projects might apply to these components. As well, unlike most forestry projects, much of the carbon sequestration of biochar is immediate: once the biochar is created and added to the soil, the increase in carbon stocks is established. However, the baseline to which this carbon stock would be compared could be part of a slower-cycling natural system, so a longer timeline is necessary to fully capture the impact of biochar, depending on what biomass is being used as a feedstock and what would have happened to it otherwise (Figure 3.2). This approach is necessary to avoid the issues outlined by Searchinger *et al*. [30], who point out that biomass energy’s “carbon neutrality” is not de-facto, but, rather, highly contingent on the baseline scenario and land-use effects (see *3.3.4 Leakage)* of fuel being collected.

To illustrate the effects of the slower dynamics of terrestrial carbon on baseline comparisons, we consider the carbon in (i) a living tree, (ii) an equivalent amount of fresh, dead herbaceous plant mass left to decay, (iii) fresh, dead woody biomass left to decay, and (iv) the amount of biochar that could be produced from the same mass of biomass (Figure 3.2). The living tree, depending on what stage it is at in its life cycle, will continue to grow and accumulate carbon, up to a point, where it stabilizes. Fresh woody biomass is modeled as decaying at a constant rate to the point where it takes decades for it to completely disappear, while fresh herbaceous biomass decays more rapidly [31, 32]. (The exact rate is highly contingent on moisture, temperature, and plant species, among other factors.) The rapid plant decay rate could also be considered to simulate the immediate carbon loss by burning. Biochar is modeled in two pools (see *3.3.3 Permanence*) [33], with a recalcitrant fraction of 0.8 [1, 34], which has a mean residence time (MRT) of 500 years [35], while the labile fraction (0.2) has an MRT of 15 years, assuming a relatively rapid turnover.

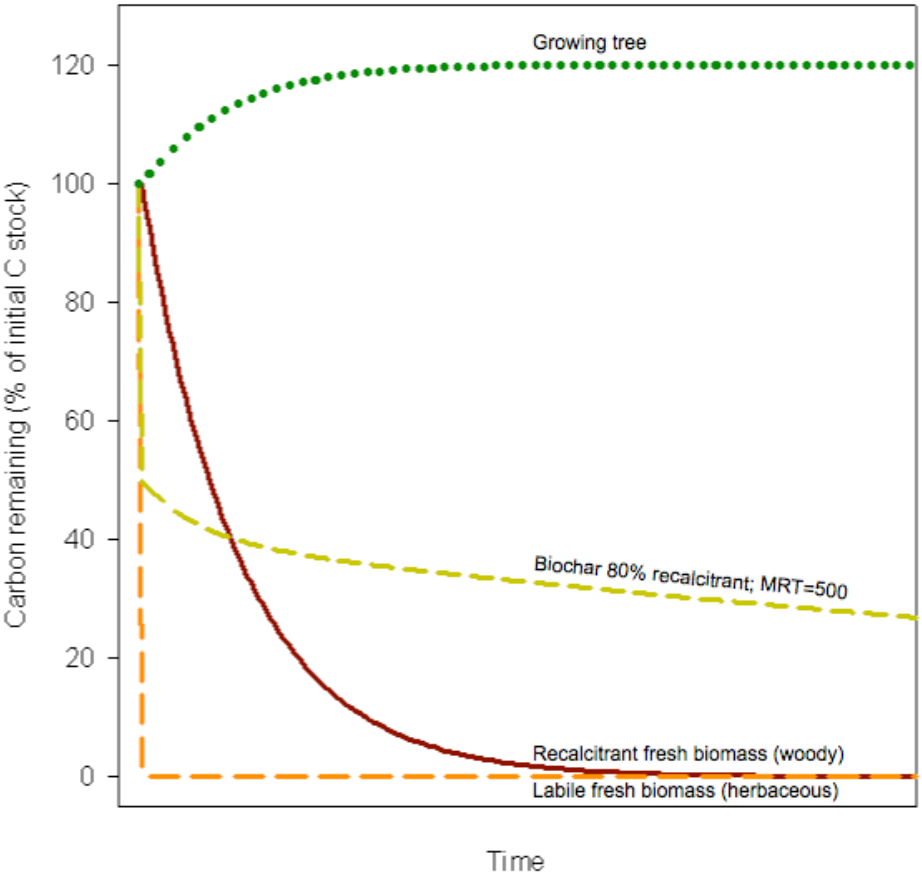


Figure 3.2. Alternative scenarios for biomass C dynamics. Each curve represents the fate of an equivalent mass of organic matter.

The first message from Figure 3.2 is that the chosen baseline scenario is very important. The amount of C maintained by biochar is immediately greater than the fresh decaying herbaceous biomass or burned biomass, but will never be higher than a living tree. The figure does not represent a system in which a new tree springs up to take the place of the one harvested (renewable biomass), and it would clearly be a mistake to consider harvesting a growing tree to “sequester” its carbon as biochar. The second message underlines the importance of the chosen timescale. While charring herbaceous biomass is almost immediately better than leaving it to decay, the initial loss of C from the biochar conversion leaves less carbon than if woody biomass had just been left to decay naturally, over the first decade or two, depending on the relative rates of decay. Taking a feedstock approach to the baseline, as described here and suggested by Sohi *et al*. [22] forces us to consider what the fate of the feedstock biomass would have been without the production of biochar, while it would be easier to ignore the feedstock source if only a total soil-carbon measurement approach is used (see *3.3.5 Measurement and Verification* for further discussion).

For projects where biomass fuel use is decreased such as with improved cook stoves, a critical factor in establishing the baseline and the number of carbon offsets to be awarded is the estimation of the fraction of fuel that comes from non-renewable biomass (fNRB) (*i.e*., being harvested faster than it is growing back) [36, 37]. As depicted in Figure 3.3, if the fuel source is renewable, then burning less of it isn’t going to differ significantly from the baseline scenario (the biomass eventually decomposes and C is released as CO_2) – only reductions in non-CO_2 emissions are counted. (One could argue that the fuel source’s living carbon stock would increase, rather than just stabilize, but conservative methodologies make the assumption that these reductions do not count toward offsets.) If the improved cook stove project reduces the use of wood fuel that was being harvested unsustainably, all emissions count as reductions.

In the following, this principle is applied to the case of biochar systems replacing biomass burning for energy, such as with cook stoves (Figure 3.4). The baseline scenario is that 6.21 t wood/year is gathered and burned in a traditional manner, producing 1.69 tCO_2e (tCO_2-equivalent emissions) /t wood of GHG if the wood is gathered unsustainably, and 0.15 tCO_2e/t wood if the wood is gathered sustainably. The first project scenario is an improved and more fuel-efficient system that uses between 90% and 15% of the wood used in the baseline scenario (open burning). Of this, 50% of the biomass is combusted and produces 1.65 tCO_2-e/t wood if the gathering is unsustainable or 0.06 tCO_2-e/t wood under sustainable harvesting practices (emission factors based on Kyoto gases in Johnson *et al.* [38]), while 50% is turned into biochar (we consider the biochar to be 100% stable, for the purposes of

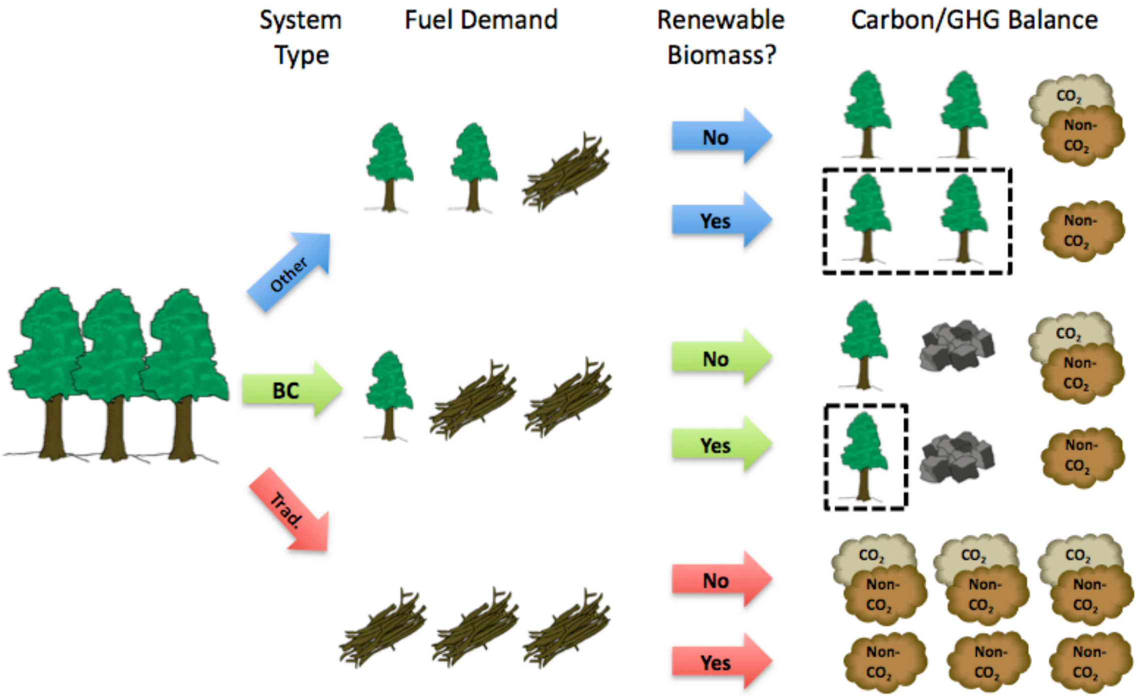


Figure 3.3. Simplified diagram of the climate change impact of three types of biomass energy systems (other improved, biochar-producing, and traditional burning). The impact of each system is considered when all fuel is renewable biomass, and when all fuel is non-renewable biomass. Dashed boxes represent C stocks that are not included in the carbon/GHG balance.

illustrating this point). The second project scenario is an improved system that does not produce biochar, and combusts the same amount of fuel as the biochar-producing system would use for fuel, minus the amount that remains as biochar, to compare both systems roughly based on their energy production. If the biomass is harvested sustainably, then any C in biochar produced counts as sequestered CO_2. If the biomass is harvested unsustainably, C in biochar is not considered to be a change from baseline. This approach is used because even though biochar would be more stable than fresh biomass on the long term, promoting unsustainable harvests to produce biochar would be problematic because there are many critical non-C benefits of sustaining living biomass stocks.

As seen in Figure 3.4, introducing a biochar system to a region where fuel biomass is nonrenewable provides the greatest impact, so the estimation of fNRB for the baseline scenario is critical. The less fuel the system requires, the greater the reductions, as with renewable biomass. The biochar-producing system can use more total fuel and result in the same impact as a system that does not produce biochar, because the portion of fuel that is turned into biochar produces few emissions. (This is at least partially offset by the fact that a biochar system would need relatively more fuel than a non-biochar system to produce the same amount of energy, which is not considered here in detail.) Interestingly, if biochar is being produced in a renewable fuel system, the more fuel that is used, the greater the sequestration impacts. Thus, in renewable systems, while non-biochar systems rely on reductions coming from marginal differences in non-CO_2 gases, biochar-producing systems have the advantage of the renewably produced biochar, making the value of a biochar cook stove project somewhat less dependent on the fNRB baseline.

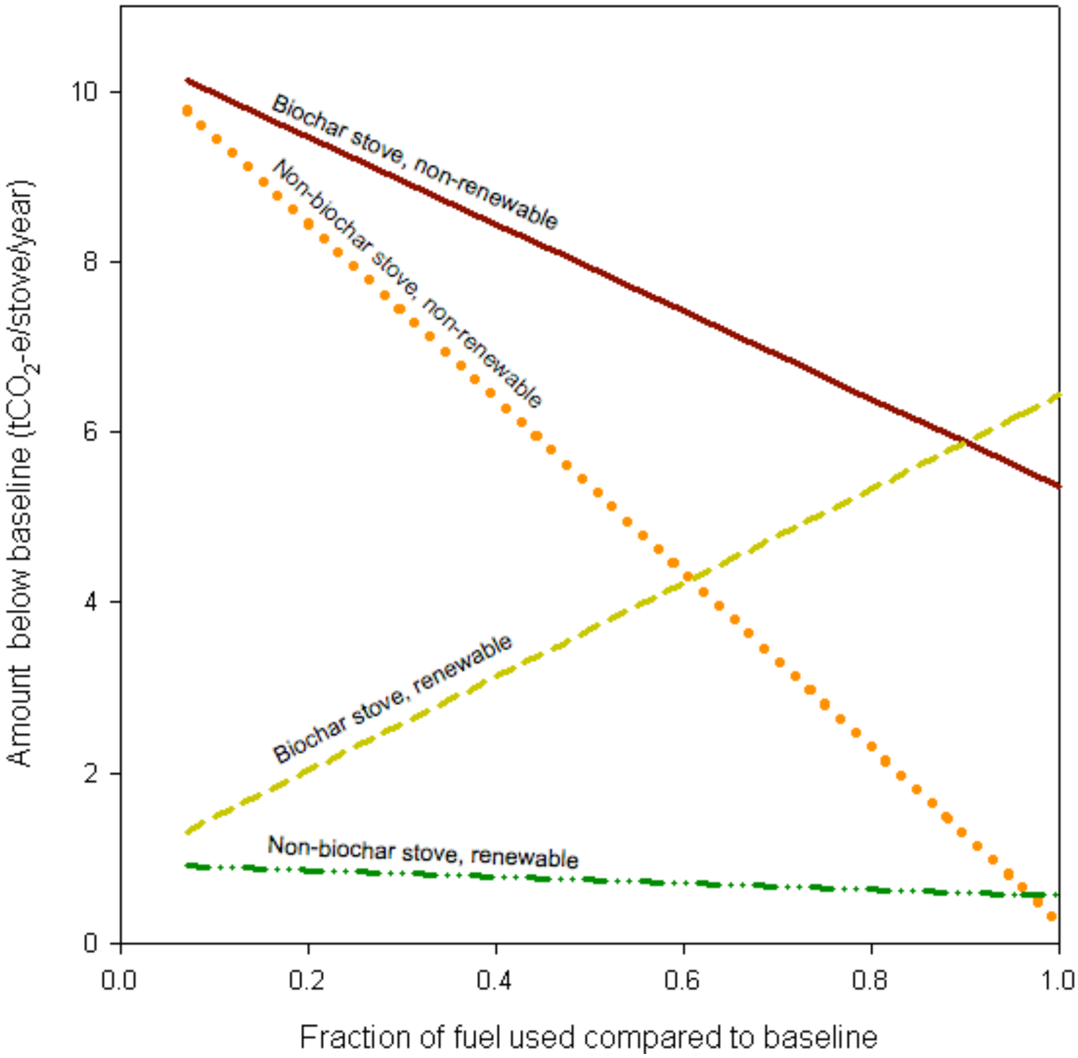


Figure 3.4. Potential deviation from baseline scenario (open burning) compared to fraction of total fuel used compared to baseline scenario, for improved biomass energy systems with and without biochar in renewable and non-renewable biomass systems. Parameters were chosen to show trends, not precise values. Note that the curves are not normalized by energy use, but by total fuel consumption.

3.3.3 Permanence

Should biochar carbon sequestration or a portion of the carbon sequestered be considered "permanent"? When we manipulate the natural cycling of carbon, this can be complicated. The most common example is afforestation: if trees are planted to sequester carbon and the associated offset credit is sold, a subsequent forest fire would release the sequestered carbon, nullifying the offset. Different methods of reducing emissions or sequestering carbon have advantages and disadvantages when it comes to permanence (Table 3.1), and all depend substantially on the baseline scenario.

Table 3.1. Permanence issues by emission reduction or C sequestration source

Project area	**Permanence issues**
Destruction/alteration of GHGs such as CH_4 from landfills	Emissions are directly reduced and are non-reversible – highly permanent
Energy use (such as increased energy efficiency or renewable fuels)	Less fossil fuel is used, but it does not stop these fuels from being used by another source in the future and producing emissions – emissions are prevented or delayed, but atmospheric CO_2 is not directly decreased
Terrestrial C stocks	Terrestrial C stocks are actually increased, drawing down the stock of CO_2 in the atmosphere, but the stock still cycles as part of the global C cycle, leaving potential for its eventual release – relevant timescale determines "permanence"

Because biochar is an organic substance, it is still part of the natural carbon cycle. Biochar is degraded by microbial as well as abiotic processes [35, 39, 40]. Although it is difficult to make generalizations about many of biochars' properties because it can be formed from many different feedstocks and applied to soils under diverse environmental conditions, in general, the decay of biochar takes place much more slowly than uncharred organic matter – MRTs for charred organic matter have been estimated to range between hundreds to thousands of years [35, 41-47]. In some cases shorter MRTs on the order of years to decades have been estimated [48, 49], particularly in short-term studies. The range of MRTs across biochars is related in part to different production conditions (particularly temperature) [10, 35], but also potentially to the heterogeneity of biochars [35]: biochar is composed of a range of different compounds [23, 50-52], some of which are more labile, and others that are highly recalcitrant. Thus, it is necessary to develop ways of predicting a given biochar's stability. This characterization could be more easily achieved in industrial-scale systems, but may be challenging for biochars produced in less uniform systems, such as cook stoves, for which greater sampling efforts would have to be made to describe an “average” biochar.

A first step approximation to understanding biochar stability may be to use a two-pool model, where biochar is modeled as having a relatively labile fraction and a recalcitrant fraction [33], which could account for some of the range in measured MRTs between short-term and long-term incubations. We investigate how varying the stable fraction in a two-pool model and varying the decomposition rate affect C storage in Figure 3.5. Considering first the effect of varying MRT, we see in Figure 3.5 that a biochar with an 80% recalcitrant fraction and a mean residence time of 100 years would show decomposition of 86% of the sequestered carbon within 200 years, whereas a biochar with a mean residence time of 500 years would lose only 34%. Thus, on a carbon crediting timescale, MRTs of a few hundred years may suffice to provide effective permanence for a large fraction of the biochar’s carbon. Within the modeled range of 20 to 100% stable fraction and 100 to 1000 MRT, we see that on a 200-year timescale, sequestration is more sensitive to variations in the size of the recalcitrant fraction than mean residence times, particularly once the mean residence time is greater than 500 years. Thus, if the size of the recalcitrant fraction can be established for a biochar, the precise determination of its mean residence time – so long as it is greater than about 500 years – is not so critical for timescales of a century. However, if the MRT is less than a few hundred years, the establishment of both parameters begins to become important, along with the given MRT of uncharred biomass. This concept is explored further in [53], including investigation of the effect of application rates.

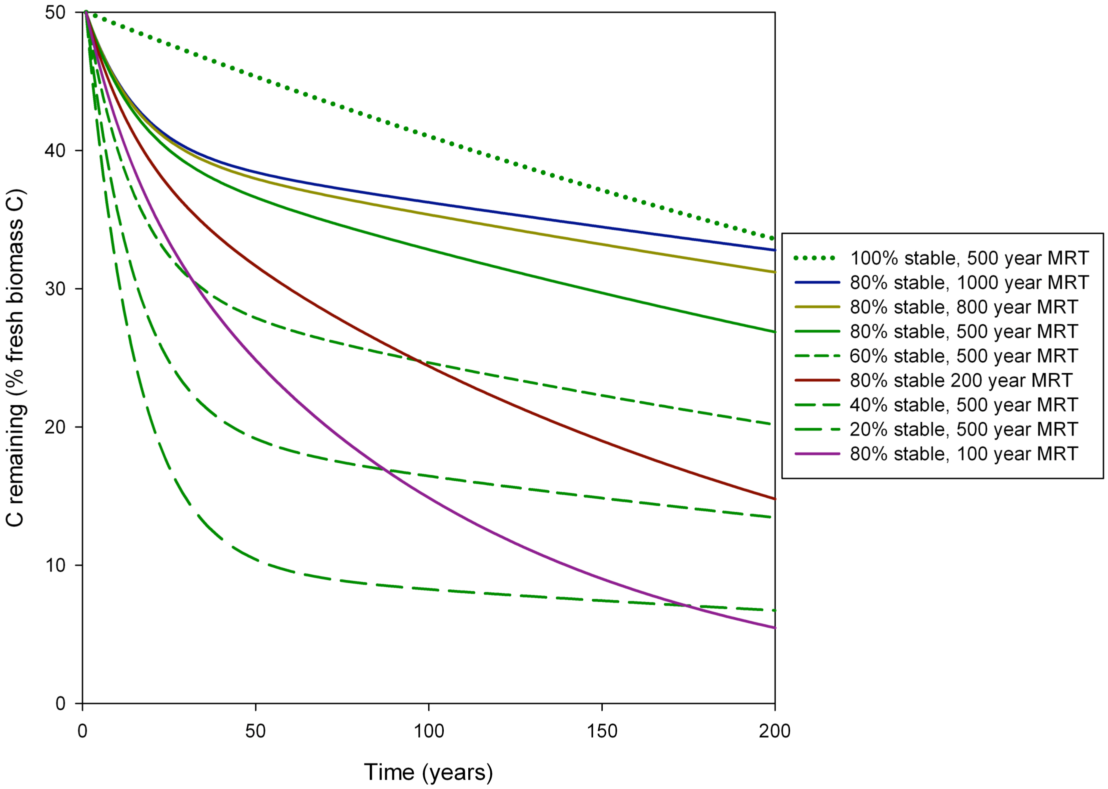


Figure 3.5. Percentage of C remaining in biochar over time, varying the stable fraction (green dashed lines at 20, 40, 60, 80, and 100% stability and a MRT of 500 years) and the mean residence time (solid lines at 100, 200, 500, 800, and 1000 years and with 80% stability)

Permanence for any long-term carbon storage project must be confirmed by determining whether the project is continuing to store carbon or when it stops to store carbon and must involve a mechanism to replace any eventual releases of stored carbon. Approaches for addressing this issue have included (i) the use of "buffers" – some credits are never sold, to make up for those that could possibly be lost, (ii) substitution – ensuring that if one project fails, another is created to take its place (risk management through a portfolio of different mitigation activities), (iii) insurance regimes and (iv) using "tonne-year accounting", where credits are valued based on the number of tonnes sequestered and for how many years they are sequestered [54-57].

The latter two options are applied at the project level, while the first two are applied at a scale where projects are aggregated. For example, forestry projects under the CDM use an approach where the carbon sequestered results in a credit that is considered temporary and expires after a designated period and must be replaced, even if the carbon apparently remains sequestered [29], while land-based offsets in the voluntary carbon market may use any or none of these approaches.

The number of credits delivered in tonne-year accounting for most terrestrial systems is highly sensitive to “equivalence time” – the number of years of storage that is deemed to constitute “permanent” sequestration [57]. This high sensitivity to equivalence time results when C turns over on timescales much faster than 100 years, and where human and natural interferences such as fires or insect outbreaks are difficult to predict. In the case of biochar, this issue is simplified because a significant portion of most biochars will remain stable for much more than 100 years, or other equivalence times that would likely be used. Determining this “stable fraction” could be sufficient to quantify the effective permanence of carbon storage using tonne-year accounting and an equivalence time of 100 years or more, making a form of tonne-year accounting a viable approach for measuring biochar projects. However, the Global Warming Potentials (GWPs) on which this concept is based are somewhat contested, due to their lack of economic rationale for the 100-year equivalence time and other issues [56, 58-62].

If one believes that an increase in carbon storage within a natural system can never be considered permanent on a relevant timescale, then we must consider whether storage for temporary credits, like the forestry carbon credits in the CDM, is valuable. In order for this to be true, purchasing a temporary credit today that will eventually expire, *plus* the cost of purchasing a permanent credit at some time in the future would have to cost less than purchasing a permanent credit today, or there would have to be some added value in temporary credits, such as ecological or agronomic benefits. Detractors of temporary credit schemes argue that in order for temporary credits to be replaced with permanent credits, regulatory mechanisms and institutions will have to be in place over very long periods of time, and the social, political, and economic uncertainty surrounding these assumptions are too great. However, this is, in essence, true of any regulatory system.

Initial analyses into this question suggest that temporary crediting would be valuable for some carbon sequestration projects [54, 56]. If we consider deep-ocean C storage, as an analogue for biochar, we can extend Herzog *et al.*'s analysis to a biochar system. This comparison is appropriate in that (i) carbon stored in both systems is very slow-cycling, (ii) human and natural interventions are unlikely to cause major unexpected loss events, and (iii) it is challenging to measure the remaining stored carbon over time directly. Because we would expect the possible C loss curves of a given biochar to be roughly similar to the oceanic C loss curves in Herzog *et al.*'s [56] analyses, we can predict that biochars with MRTs of between 150 and 575 years could be economically viable in a system where carbon offset prices remain constant, while somewhat greater stability would be necessary for systems where the price of credits rises for a number of years and eventually stabilizes. (This scenario is based on the prediction that an alternative non-fossil fuel energy source will cap the costs of abatement.)

A compromise approach for biochar projects may be a combined accounting scheme: energy-based reductions from biochar projects are judged under the same shorter crediting period as non-forestry projects, but the terrestrial carbon impact of biochar within the system accrue under longer crediting periods over which its effects last. *I.e.*, any energy-based offsets from an introduced biochar stove would result in permanent credits for the first crediting period (with option for review and renewal, based on standard re-evaluation procedures), while the emission reductions from baseline due to biochar that are produced over that time period (Figure 3.2) are designated as temporary credits initially, with a potential to be proved permanent over time. These credits would be reissued and adjusted according to the baseline after each crediting period, regardless of whether the energy-based offsets are renewed. The size of the biochar credits would be expected to grow initially, as their divergence from the baseline biomass scenario would increase over time, so each crediting period would more than replace the credits issued in the previous period (Figure 3.6 – no project renewal). If review of the baseline scenario for the energy-based reductions results in renewal of the biochar project, then the biochar generated from this period would also be counted in future crediting periods (Figure 3.6 – 1 project renewal). This approach accounts for economic and technological baseline uncertainties while allowing for the slower dynamics of natural systems to be accounted for at the same time. While scientifically appropriate, temporary credits have proven to be a hurdle for the success of forestry projects in terms of policy and market access. For biochar, it would be scientifically robust for the number of crediting periods to be substantially higher than is currently standard, as its effects would be expected to persist for very long periods of time and it would not be subject to the same uncertainties as other terrestrial C projects. After having established their persistence over a designated number of renewal periods, the credits could eventually be designated as permanent. This could allow biochar to succeed where other terrestrial carbon sequestration schemes – such as no-till agriculture or afforestation/reforestation – have struggled to guarantee long-term carbon sequestration.

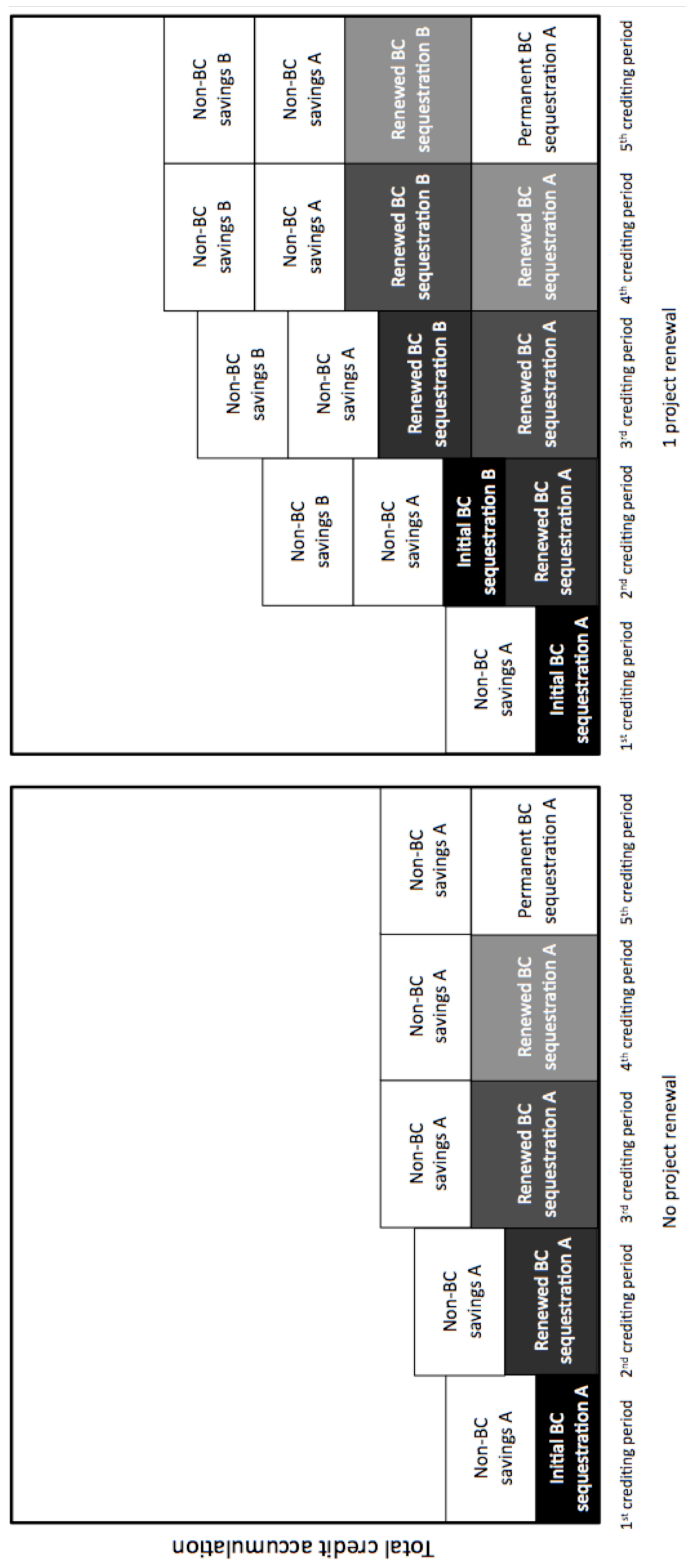
For biochar projects outside of offsetting schemes, the question of permanence is less critical – the biggest question is whether we are optimally managing terrestrial carbon. For offsetting projects, however, it is critical, because emissions are being released elsewhere – permanently – in the place of the project. Without the driver of carbon offsetting finance, biochar projects may be less economically attractive and would rely more heavily on the value of their co-benefits, such as energy production, soil improvement and organic waste management.

3.3.4 Leakage and system drivers

Leakage occurs when a project that reduces emissions within a boundary produces unintended changes elsewhere (spatially or temporally) that result in higher net emissions than predicted. An example is the situation when groups in developing countries without Kyoto commitments clear native forests to make way for creditable CDM afforestation and reforestation projects [63]. Within the compliance offset market, these unintended consequences are a problem twice over – first, because of the direct impact they have in the area of leakage, and second, because the supposed reduction was credited against allowed emissions under the carbon trading scheme. These effects can be captured by the use of life cycle assessments (LCAs) or other system analyses, but this requires the consideration of effects beyond typical project boundaries, which may be difficult to identify.

Besides acting as a very stable pool of carbon, biochar may interact with the soil and climate system in other ways that need to be investigated when measuring its net impact. The magnitude of biochar loss to the atmosphere as particulate black carbon or its effects on soil N_2O, CH_4, and CO_2 emissions are generally poorly characterized and are an important area for future study before wide-spread application is advocated. Black carbon particles in the atmosphere are known to increase radiative forcing and although they have a much shorter mean residence time than most GHGs, when they settle out of the air, they decrease the albedo of land surfaces, particularly in the polar regions [64-66].

Figure 3.6. Possible crediting scheme for biochar projects. White rectangles represent permanent credits, while grey and black rectangles represent temporary credits.


Total credit accumulation
Non-BC savings A
Initial BC sequestration A
Non-BC savings A
Renewed BC sequestration A
Non-BC savings A
Renewed BC sequestration A
Non-BC savings A
Renewed BC sequestration A
Non-BC savings A
Permanent BC sequestration A
1st crediting period
2nd crediting period
3rd crediting period
4th crediting period
5th crediting period
No project renewal
Non-BC savings A
Initial BC sequestration A
Non-BC savings B
Non-BC savings A
Initial BC sequestration B
Renewed BC sequestration A
Non-BC savings B
Non-BC savings A
Renewed BC sequestration B
Renewed BC sequestration A
Non-BC savings B
Non-BC savings A
Renewed BC sequestration B
Renewed BC sequestration A
Non-BC savings B
Non-BC savings A
Renewed BC sequestration B
Permanent BC sequestration A
1st crediting period
2nd crediting period
3rd crediting period
4th crediting period
5th crediting period
1 project renewal

Empirical evidence has been shown where N_2O emissions in biochar- amended soils were reduced in several cases [67-70], but are increased in others, particularly at high moisture contents [67] or following a large addition of nitrogen [69]. Studies have noted variable CH_4 responses, with some decreases [71, 72] and other increases [68, 70]. This issue could be addressed by current CDM methodology, which allows for direct CH_4 emissions from pyrolysed organic matter to be neglected when the volatile carbon to fixed carbon ratio as determined by the American Society for Testing and Materials International wood charcoal analysis is less than or equal to 50% [73]. However, this methodology would not address its potential impacts on existing soil organic matter (SOM). The effect of biochar on native organic matter decomposition to CO_2 is also not fully understood. Some studies [48, 74, 75] have observed increased CO_2 emissions or C loss when fresh biochar was added to soils, and thus suggest that the biochar stimulated the decomposition of existing SOM or fresh residue on the soil surface. Contrary to these results, Kuzyakov *et al*. [46] found no stimulation of SOM decomposition by biochar, while Liang *et al*. [76] found that fresh organic matter was incorporated into aggregates more quickly in soils with high biochar contents, protecting SOM. As a rule, if potential soil emissions were expected to decrease for a given biochar-soil pair, it would be acceptable to ignore them or include them as additional emission reductions if they can be verified, but if it seems that emissions may be higher upon biochar addition, then it is essential that they be quantified. This could be achieved by establishing a control plot to determine what the baseline emissions would have been, but this approach would be time- and cost-intensive. Current research is investigating these issues, and must continue to improve our understanding of not only the GHG effects of biochar application to soils, but also the mechanisms behind these effects. Once a categorization of emission profiles for different biochar-to-soil-application situations exists, conservative default values could be used to overcome time- and cost-intensive requirements for measurement.

Returning to the biochar cook stove example, if a decrease in fuel use due to greater fuel efficiency simply allows other groups to burn more wood than before, then the emission reductions could be overestimated. A second potential leakage factor is the "rebound effect" – because the new stoves are more efficient, users may cook more. This factor is investigated in Figure 3.7. Based on the same values as Figure 3.4, the amounts by which cooking activity would have to increase to completely negate the improvements made by a more efficient stove were determined. The renewable biomass biochar stove is not shown here, because increasing stove use would actually increase C sequestration.

As seen in Figure 3.7, at relatively high fuel efficiencies, cooking activity would have to increase many times to cancel out emission reductions, whether renewable biomass or non-renewable biomass is being used. Although the net reductions in a non-biochar renewable fuel system are lower, such a system is less sensitive to the rebound effect, due to wider margins in GHG emissions from non-CO_2 gases. These data indicate that the rebound effect would likely not render a cook stove project's emissions reductions null, because we would expect there to be a limit on how much food would ever be cooked, and so the introduction of a biochar cook stove would be unlikely to act as a driver for increased biomass use. This is an example of "safe use" – where the driver of the system places a limit on its activity.

If the driver for a system were energy production, as would be the case for an industrial biochar production system, the constant demand for energy would result in a push towards increased biochar production, increasing the demand for feedstocks [77]. One of the major critiques of biomass use in biofuels is the direct effects of crop residue removal from soils, which stops the necessary return of carbon and other nutrients to the native system as well as the loss of numerous benefits of residue retention on soils, such as protection from erosion [78, 79]. In addition, the indirect effects of the creation of a market for biofuels can act as a driver for other negative processes, such as the clearing of forest for devoted biofuel crops, such as sugar cane production for ethanol or oil palm for biodiesel [80]. To avoid these negative impacts, projects should be designed where biomass sources are used explicitly to exclude these effects by using particular kinds of waste streams, which can be considered "true wastes".

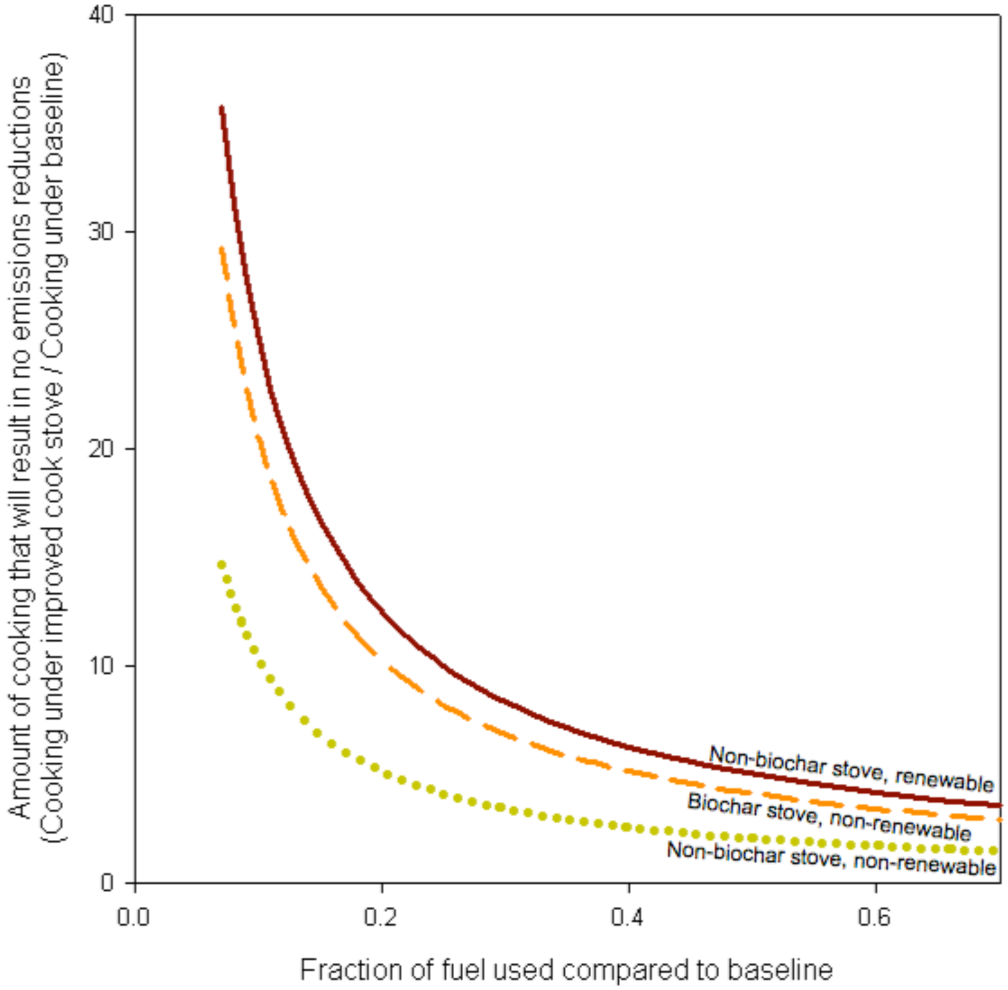


Figure 3.7. Increase in cooking activity that would increase total emissions by an amount equal to the emission reductions from increased efficiency. Note that the curves are not normalized by energy use, but by total fuel consumption.

In the industrial biochar system where switchgrass is used as a feedstock, Roberts *et al*. [1] investigated the impact of including direct and indirect land-use changes associated with changing cropland to biofuel plantations and replacing the displaced crops. When this impact was included, it increased calculated net GHG emissions by over 100%. If an offsetting project had not included this impact, it would have had significant leakage. In this same system, if residential yard waste were used as a feedstock, it would be highly unlikely to become a driver for increased production of yard waste. Although it could be argued that the export of nutrients through lawn clippings and raked leaves is undesirable, it seems improbable that, for example, the revenue the city derives from this alternative waste management system would result in convincing residents to refrain from converting their lawns to more natural systems or deciding to maintain a park's playing field instead of allowing it to revert to forest. Furthermore, the resulting biochar product could be re-distributed to citizens for application to their lawns, partially closing this loop, as is done in some municipal composting programs [81]. Returning biochar from true waste feedstocks would allow for a significant portion of C and some other nutrients, particularly phosphorous, to be returned to the land, resulting in a "closed loop" system, whereas they might have ordinarily been lost [22].

We combine these two factors – "true wastes" and alternate system drivers – to create a conceptual "safety matrix", predicting which systems would be more sustainable and which would have high potential for unsustainable expansion or significant land-use changes (Table 3.2). The potential for leakage is not, in itself, a problem. It can be predicted using methods such as those investigated above, and accounted for using estimates that will result in conservative predictions of emission reductions. It is only when it is neglected that negative consequences occur.

Table 3.2. Safety matrix of feedstock and system drivers for biochar-producing systems

	Feedstock	
System Driver	“true waste”	Purpose-grown
Cooking energy (“Safe usage”)	Banana leaves in cook stove (low risk)	Biofuel tree plantations for cook stove (medium risk)
Energy production	Yard waste in industrial pyrolysis plant (medium risk)	Switchgrass for industrial pyrolysis plant (high risk)

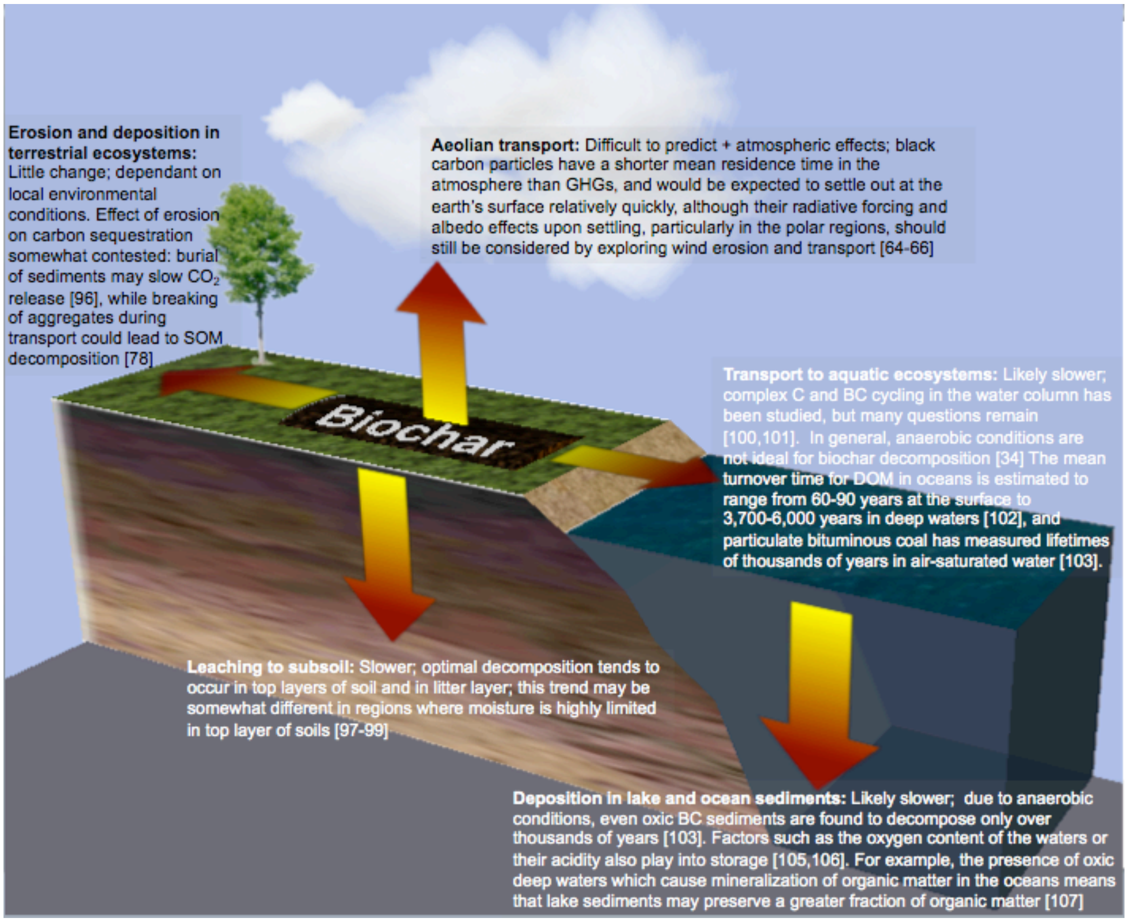
3.3.5 Measurement and verification

We divide approaches to measuring the biochar that is produced in a given system into two broad categories: it could be measured during production and soil application, after which its long-term deviation from the baseline scenario could be predicted (indirect measurement), and it could be measured directly in the soil over a number of years [22]. Direct measurement is attractive from a scientific point of view because it helps establish a concrete estimate of the longevity of biochar, but it may be problematic in terms of costs associated and in systems with high spatial heterogeneity of soils or biochar application, requiring the analysis of many soil samples (see Mooney *et al*. [82] for discussion of costs of soil sampling for soil carbon sequestration). Direct measurement may also be challenging in systems with high losses through erosion or leaching. Charcoal has been shown to erode preferentially over other soil components in some systems [83, 84]. As well, in one study where biochar was added to a Colombian savannah Oxisol, the most significant biochar losses from the system (20-53%) were attributed to runoff, and biochar was shown to leach through soils as both dissolved organic matter (DOM) and, to a lesser extent, particulate organic matter [47]. If the biochar is transported from the system, but is not lost as CO_2, direct measurement would result in dramatic underestimates of its longevity.

It could be preferable to use indirect measurement of biochar to measure its impact. Because the reduction in CO_2 can be measured as the difference from a baseline scenario where the biomass decays or is burned [22], rather than the increase in soil carbon stocks, whether 100% of the biochar remains in the soil where it is applied may not be a critical question, so long as it can be established that any transport from the system would be likely to decrease the rate of decomposition to CO_2, rather than increase it. We explore this question in Figure 3.8, considering transport through erosion, through leaching, to lake and ocean waters, to lake and ocean sediments, and to the atmosphere. From what we know of these zones, we predict that the zone where biochar would be applied – the top layers of soil – is likely the most conducive zone for organic matter decomposition.

While verifying the amount of biochar present in a soil is feasible (see [22, 85] for a discussion), using this metric for the total biochar storage while ignoring erosion or leaching losses may not be a good way to estimate whether the carbon in the biochar is still sequestered for some systems. Monitoring direct biochar production and using decomposition studies [35, 46] could be a more accurate and less expensive predictor, combined with a minimal degree of soil sampling to establish that biochar is being applied to soil, and not, for example, being used as fuel. Developing confidence in this approach would be instrumental in maximizing biochar's potential as a carbon sequestration mechanism and is a research challenge for the future.

Based on the principles outlined thus far in this article, we propose that accounting for carbon credits issued for biochar production might be structured around the approach outlined in Figure 3.1. Measurements of crop yields and GHG emissions from the soil where biochar is applied are measured using control (untreated) plots and biochar plots. The biochar itself is compared to the baseline scenario of predicted biomass decay or loss by burning in the given environment, based on an indirect measurement of a proportion stable C fraction and its MRT, through incubations or other predictive measures. This approach focuses on the carbon directly sequestered in biochar, and would be nested within the broader project assessment, which would also include direct emissions reductions and fossil fuel displacement or efficiency improvements.



Erosion and deposition in terrestrial ecosystems: Little change; dependant on local environmental conditions. Effect of erosion on carbon sequestration somewhat contested: burial of sediments may slow CO_2 release [96], while breaking of aggregates during transport could lead to SOM decomposition [78]

Aeolian transport: Difficult to predict + atmospheric effects; black carbon particles have a shorter mean residence time in the atmosphere than GHGs, and would be expected to settle out at the earth's surface relatively quickly, although their radiative forcing and albedo effects upon settling, particularly in the polar regions, should still be considered by exploring wind erosion and transport [64-66]

Transport to aquatic ecosystems: Likely slower; complex C and BC cycling in the water column has been studied, but many questions remain [100,101]. In general, anaerobic conditions are not ideal for biochar decomposition [34] The mean turnover time for DOM in oceans is estimated to range from 60-90 years at the surface to 3,700-6,000 years in deep waters [102], and particulate bituminous coal has measured lifetimes of thousands of years in air-saturated water [103].

Leaching to subsoil: Slower; optimal decomposition tends to occur in top layers of soil and in litter layer; this trend may be somewhat different in regions where moisture is highly limited in top layer of soils [97-99]

Deposition in lake and ocean sediments: Likely slower; due to anaerobic conditions, even oxic BC sediments are found to decompose only over thousands of years [103]. Factors such as the oxygen content of the waters or their acidity also play into storage [105,106]. For example, the presence of oxic deep waters which cause mineralization of organic matter in the oceans means that lake sediments may preserve a greater fraction of organic matter [107]

Figure 3.8. Predicted effect on rate of decomposition after biochar transport, based on rates for non-BC organic matter and charcoal [34,77,63-65,95-106]. (Components of model by Yiperoo and Marub, from Google 3D Warehouse).

3.3.6 Economics

The economics of biochar systems is a nascent field of research. Particularly, the potential income of carbon assets generated by different biochar systems or their different components is not yet fully researched. In essence, the total value of the carbon asset generated by a biochar system would depend on the development and application of baseline and monitoring methodologies or methodology tools (*i.e.*, modules) to capture those value streams. A methodology creates a carbon asset by clarifying approved procedures to determine emission reductions from a project activity over time. Carbon assets can then be used as offsets for means of compliance or for voluntary reasons

Currently there are over 120 active and approved CDM methodologies - covering a wide variety of project types and technologies (sectoral scopes) but none has been approved for biochar so far. A first attempt has been made under the Voluntary Carbon Standard (VCS) (a carbon offset standard for the voluntary market) [86]. This submission is a large scale methodology quantifying the GHG emission reductions from the production and incorporation of biochar into soil in agricultural and forest management systems, using a biochar production system that is conceptually similar to the industrial system considered in Roberts *et al.* [1]. The first VCS assessment of this methodology is ongoing and the market relevance of this methodology has yet to be seen. An important starting point for any biochar cook stove methodology would include the Gold Standard (another carbon offset standard)'s *Indicative Programme, Baseline, and Monitoring Methodology for Improved Cook-Stoves and Kitchen Regimes* [37] and the CDM's *Energy efficiency measures in thermal applications of non-renewable biomass* [36].

By developing a methodology, a project proponent develops a public good, since once the methodology is approved it can be used by any other project developer as well. Hence, there is no clear first mover incentive for entities proposing methodologies, even more so because costs to develop a new methodology can be substantial. A recent World Bank report looking back on ten years of carbon finance operations assesses the approximate costs for the development of a new methodology at US$125,000 for both large and small scale methodologies with even higher costs typically incurred for methodologies for afforestation and reforestation projects [87]. According to the same analysis, it took approximately two years for a new methodology to be developed, from inception to approval. Since the methodology costs analyzed above refer to the CDM, which has proven to be a rather lengthy and hence costly process, one could hypothesize that the costs for a VCS-type biochar methodology may be slightly lower than the above figure. Still, there are new aspects of biochar systems that need to be captured methodologically so that costs and resource demands to develop a new biochar methodology (or tools / modules) could still be substantial. Clear incentives to develop broader and more widely accessible methodologies or methodology tools are still missing, at least under the current CDM framework, which considerably hinders innovation. However, just recently the VCS proposed an innovative compensation mechanism for methodology developers by reimbursing part of the incurred costs through a levy on Voluntary Carbon Unit (VCUs), the VCS-specific carbon asset. From an economic perspective this idea seems to be promising and could spur the development of a biochar-related methodology since biochar assets created under this new methodology would refund the biochar methodology developer.

To date, the economics of process in- and outputs of industrial-scale biochar systems have been analyzed in greater detail (*e.g.* [1, 88]) than the economics of small-scale biochar systems such as cook stoves at household level, for which such analyses are almost non-existent. Cost factors covered in the industrial-scale biochar system analyses are for production and collection of feedstock, feedstock transport, possible storage and (pre)-processing of feedstock, costs of the pyrolysis operation itself, biochar transport, and the subsequent biochar application to fields. These cost factors are compared with the benefits of selling energy created during the exothermic pyrolysis process, biochar-related cost-savings through improved fertilizer use efficiency, the value of the N and P content of the biochar, as well as the carbon asset generated by the biochar operation. Possible additional revenues can be tipping fees in the case of a biomass waste-to-biochar management scenario. Overall, Roberts *et al.* [1] found that transportation distance has a significant impact on costs, which coincides with the findings of McCarl *et al.* [88]. Also, pyrolysis plant fixed and operating costs as well as energy prices are important factors for the economic viability of biochar systems at larger scale. Roberts *et al.* found that the break-even prices were \$40/t CO_2e where corn stover is used as the pyrolysis feedstock and \$62/t CO_2e for a switchgrass scenario, but only \$2/t CO_2e for yard waste [1]. In general, situations where feedstock is available only as decentralized field residue that needs collection and transport seem less economically attractive than scenarios involving more centralized process residues or waste streams that have low transportation requirements.

An area that has not been captured by the current economic analyses of biochar systems from a carbon finance perspective are the costs involved to prepare the necessary documentation to credibly demonstrate the creation of a carbon asset. Under the CDM this would mean the preparation of a project design document (PDD) including a description of the baseline and monitoring methodology to be used, an analysis of environmental impacts of the proposed project, comments received from local stakeholders and a description of new and additional environmental benefits that the project intends to generate. Official data on actual costs for PDD preparation of CDM projects are somewhat scarce. Costs vary to a great extent depending on the project's complexity (*i.e.*, project size and sectoral scope or technology) as well as the experience of the project entity preparing the PDD. For biochar operations, as a newly emerging project category, PDD costs of US$ 20,000 to US$ 50,000 do not seem to be unrealistic. This does not include the development and approval process of the underlying methodology, which is the basis for a successful PDD completion in the first place.

The preparation of a PDD is followed by what is called validation and registration of the project. During validation, an independent entity reviews the aforementioned project documentation and provides an opportunity for public comments. The project site is also visited. After that, the validator (or designated operational entity, in CDM terminology) will forward all documentation to the CDM's Executive Board for formal registration [89]. Early experiences from the CDM show that validation and registration can cost between US$ 15,000 to US$ 25,000 for large-scale CDM operations with small-scale operations not lagging much behind [87].

Once a project is operational, successful implementation and carbon asset delivery depend on adhering to a pre-defined monitoring plan. The monitoring plan specifies all variables to be measured over time and the frequency of measurement. Failure to comply with the monitoring plan means that the reported emission reductions may be disputed, resulting in possibly substantial discounting of the carbon asset, which would have negative consequences on the project's cash flow. The monitoring report is the basis for successful verification and certification of the project. After that, 'issuance' can be requested, where ERs are distributed to project participants and proponents as requested. Detailed costs for the latter process steps toward the establishment of a carbon asset are difficult to obtain. However, Figure 3.9 gives an overview of costs per expected tonne of CO_2e contracted according to different project types within the World Bank's carbon fund portfolio [87]. The differences in unit project costs largely correlate with project size. While initial project development costs have been higher, on an absolute basis, for the industrial gas projects, the unit cost is still very low due to the volume of expected emission reductions from these projects. In other words, technologies that provide for larger scale projects generate more emission reduction credits, thereby allowing the fixed costs to be spread. For biomass energy, the project development costs are in the range of US$ 0.5 per expected tonne of CO_2e generated. For forestry operations, the limited data sources available indicate that preparation costs are even higher than for wind energy, *i.e.*, above US$ 0.8 per expected tonne of CO_2e generated. At the same time, Johnson *et al*. [38] predict a $8/t$CO_2$-e cost for their cook stoves, under a conservative (60%) adoption rate over a 7-year crediting period and including project establishment and monitoring costs, but not including other bureaucratic costs. Where exactly a biochar operation would fit into this cost spectrum is difficult to tell with certainty.

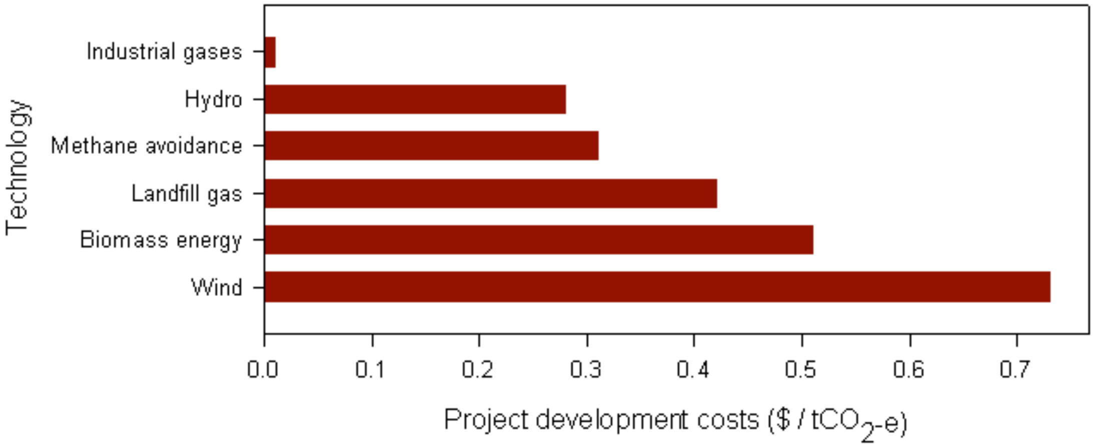


Figure 3.9. World Bank greenhouse gas mitigation project development costs by technology (n=53) [94].

Assuming from the discussion above that individual biochar projects, particularly cook stove applications, would generate fewer ERs as compared to industrial gas projects, project development costs would be greater. If a biochar cook stove produced greater ERs than another improved cookstove, we could expect a lower per-tCO_2-e price, but if the increased complexity of the system resulted in higher monitoring costs, then prices would increase. At the same time, distinct monitoring advantages for biochar-to-soil applications like indirect monitoring, as discussed earlier, or mid-infrared spectroscopy, as discussed in Manning and Lopez-Capel [85], indicate that biochar C sequestration in soils could be monitored more efficiently compared to other soil or forest sequestration, which would be an argument for lower project development costs in biochar. Thus, one could assume that project development costs for a biochar-to-soil carbon asset would imply costs in the range of US$ 0.55 to 0.85 per expected tonne of CO_2e generated, with still higher costs for stove-based biochar projects, at least initially, with costs decreasing over time as the technology is applied more widely. The more C value streams a biochar methodology would be able to capture, the lower the unit costs would turn out to be.

3.3.7 Coupling carbon credits with development

Many climate change-mitigating projects are coupled with development goals, as typified by the CDM. It is an obvious synergy to aim for, facilitating the "leapfrogging" of fossil fuel-based technology and using climate financing to promote development simultaneously with mitigation. Using finance through the carbon market to access biochar stove technology has the potential to reduce respiratory infections, reduce the impact of fuel gathering on women, or improve soil for agricultural production [3]. In that sense, true win-win situations could be created. Indeed, development must be at the core of climate change mitigation projects that are implemented in the developing world, because manipulating the way some of the poorest people in the world would live, solely in order to reduce GHG emissions so countries and firms in the global north can continue to emit, is clearly unacceptable. This is particularly important for biochar projects, because they may involve altering the stocks and flows of biomass upon which people (and natural systems) depend or promoting lifestyle changes.

In order for climate change mitigation projects to achieve sustainable development goals, their design and implementation must include the people who will be involved or affected, whether in a developed or developing country. Indeed, such an approach will likely lead to a more successful project [90]. Unfortunately, even in the short time they have existed, there is already a history of infringement on people's rights in some offsetting projects, such as the imposition of carbon-reducing projects on indigenous peoples without their consultation or involvement in the design and implementation [91, 92]. For example, Sutter and Parreño [93] assessed 16 CDM projects and found that while 72% of the total ERs were likely to be real and measurable, less than 1% of the predicted sustainable development impacts were realized. The implementation of any biochar project in developing countries must be viewed only as a stepping-stone along a self-determined path of development, and not to constrain people a low-carbon technology.

3.4 Conclusions

Developing biochar projects to mitigate climate change and their associated methodologies is a complex undertaking that requires consideration of a broad suite of issues, a number of which are summarized in Table 3.3, along with the risks and recommendations associated with each. Moving forward, the most pressing issue is the development of robust methodologies for measurement and prediction of biochar stability, based on the concepts of a stable fraction and permanence developed in this article, in order to establish a robust methodology for quantification (Figure 3.1). The effective permanence and value of carbon assets from biochar systems must be derived through careful drawing of baselines, wide system boundaries in order to

Table 3.3. Offsetting issues, risks, and recommendations for biochar systems

Issue	**Risk source and level:** **High(H)** **Med (M)** **Low (L)**	**Recommendations and Cost/Difficulty of addressing:** **High(H)** **Med (M)** **Low (L)**
Baseline Establishment	Selecting feedstocks that would result in a lower baseline than project scenario [H]	Careful system design and use of a combined baseline approach [L]
Permanence	False application of "permanence" to natural carbon cycle; failure to replace temporary credits [M]	Combination of full and temporary credits, based on stable fraction of biochar and its MRT [H]
Measurement and Verification	Difficulty quantifying net GHG emissions changes in soil system; loss of biochar from the system through erosion or leaching [H]	Measurement of biochar production, with soil samples to ensure its application, combined with full life cycle assessment and further development of field research to allow for conservative assumptions or measurement methodologies regarding non-CO_2 gases [H]
Leakage	Failure to account for direct and indirect land-use change effects; poor estimate of fraction of non-renewable biomass; rebound effect [M]	Full life cycle assessments; conservative estimates of non-renewable biomass fraction; measurement and estimation of rebound effect; system design focusing on "true wastes" and "safe usages" [M]
Additionality	Co-benefits of biochar beyond carbon could become enough to drive biochar system development alone; biochar technology becomes commonplace [L]	Use of CDM additionality tool; monitoring trends of implementation of biochar systems without carbon offset financing or changes in the barriers and current practices [L]
Economics	Project development costs are not well characterized but may be relatively high; low incentives for methodology development [N/A]	If more climate-related carbon value streams are captured, project costs will be reduced; providing incentives for methodology developers [N/A]
Development	Interference with local and indigenous peoples' ways of life, ecosystem manipulation [M]	Place development before carbon reductions; use stakeholder consultation [L]

minimize leakage, and focus on "safe systems" from the outset. Ideally, this may be achieved by designing systems based around "safe usage" system drivers and "true waste" feedstocks, with human rights as the primary consideration for any development-based projects.

3.5 Future perspective

Carbon offsets are a fast-developing field, within which biochar systems are quickly evolving. Biochar was barely on the global radar five years ago, and today it has evolved into a global phenomenon, eliciting attention from figures ranging from James Lovelock [94] to Al Gore [95]. At this pace, it could gain considerable prominence by 2020, with on-the-ground implementation of a wide range of biochar-producing systems, further developments in our understanding of its interactions with the soil and its net impact on greenhouse gases. At the same time, while many aspects of biochar position it to be an exciting component of an overall climate change mitigation strategy, a number of important questions remain, and it is essential that critical issues such as the direct impacts of variable biochar properties on diverse soil types are evaluated and controlled as such projects become more widely implemented and that the pitfalls associated with many biofuel systems are avoided. We might hope to see the development of a biochar characterization rubric and a code of best practice completed within the decade, allowing for a safe and regulated implementation of biochar systems.

Carbon markets have proved volatile over the past decade, and their dynamics will certainly affect the degree to which biochar systems are included in carbon offsetting mechanisms. While recommendations push for increasing regulation of GHGs, the inclusion of offsets in future international climate change agreements is not absolutely guaranteed. However, as climate change will certainly continue to be a major global issue, the existence of voluntary carbon markets and other sub-international carbon offsetting systems will likely provide a platform for continued offsetting projects. Increasing public awareness will probably lead to more stringent regulation of offset projects in the future as well as further emphasis on projects that have additional value beyond GHG mitigation, such as the potential agronomic benefits associated with biochar

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APPENDIX 1.1

SUPPLEMENTARY PAPER: BIOCHAR – ONE WAY FORWARD FOR SOIL CARBON IN OFFSET MECHANISMS IN AFRICA?[4]

Abstract

The Kyoto Protocol's Clean Development Mechanism (CDM) has had relatively little success in Africa due to a number of factors. Increases in agricultural soil carbon have strong benefits for soil health as well as potential for carbon sequestration, but such projects are currently excluded from the CDM and other offset mechanisms. Small-scale biochar systems with net emission reductions may hold a key for Africa to engage with the international offset mechanisms and open the door to soil carbon sequestration projects.

A1.1.1 Introduction

The benefits promised for Africa by the Kyoto Protocol's Clean Development Mechanism (CDM) have not materialized, in large part due to its failure to include projects suitable to the region. Soil carbon sequestration through biochar projects may offer a way forward for Africa's participation in offset mechanisms under the next international agreement, through a modified CDM or an agricultural parallel to Reducing Emissions from Deforestation and Degradation (REDD) projects, as well as voluntary emissions offset markets.

Offset mechanisms allow parties with emissions reduction targets to meet a portion of their targets by purchasing emission credits that are generated through the

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implementation of greenhouse gas (GHG)-reducing projects, rather than making the reductions themselves. The Clean Development Mechanism is an offset mechanism under the Kyoto Protocol where projects in developing countries may generate Certified Emissions Reductions (CERs) which can be sold to countries with emissions reduction targets. It was designed to stimulate sustainable development in developing countries by providing finance for technologies and opening an otherwise unaffordable path to clean development, while developed countries gain access to lower-cost emissions reductions, increasing the efficiency of global GHG reductions (UNFCCC, 1997). Unfortunately, to date, the CDM has failed to help many of the countries that are most in need: a meagre 2% of all registered projects have been in Africa (Figure A1.1.1), home to many of the least developed countries (LDCs) (UNFCCC, 2009a).

Although likely modified from their current forms, offset mechanisms will probably be included in the post-Kyoto international climate change agreement. Negotiations leading to the new post-2012 agreement have had a significant focus on REDD. Whether incorporated as a new type of offset mechanism or as a separate project, forest projects are likely to constitute an important piece of this agreement. However, for a number of reasons, REDD may be no more promising for African nations than the CDM was, particularly in the near term. Recent attention to biochar under the UNFCCC raises the issue of how it might fit into the framework through offset projects and whether it could provide real benefits in Africa.

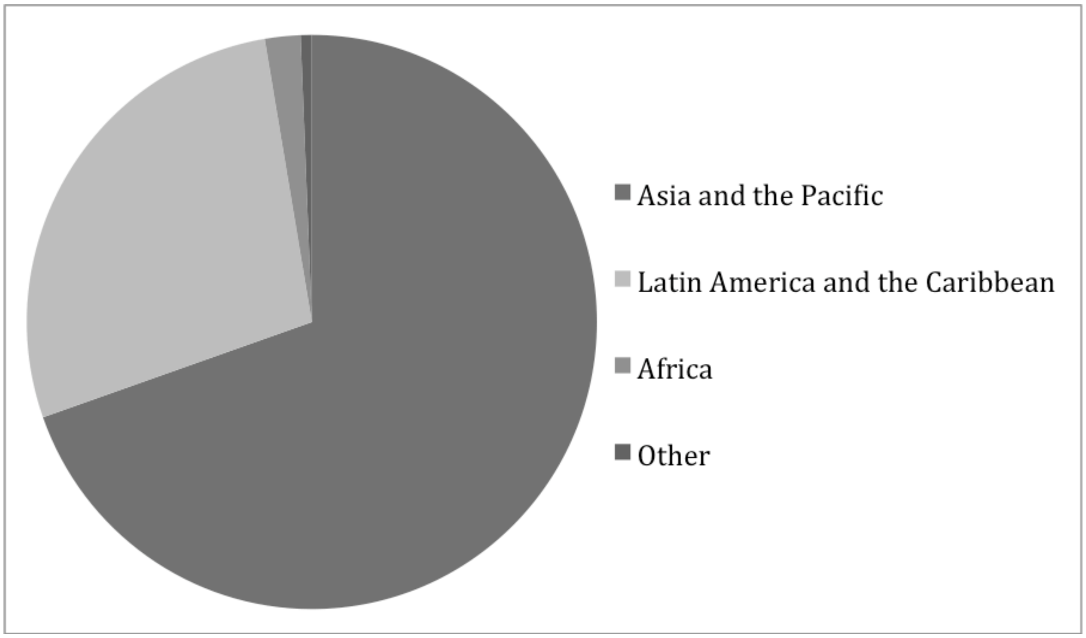

Figure A1.1.1. CDM project distribution by region (March, 2009) (UNFCCC, 2009a)

A1.1.2 Barriers to Africa's involvement in offset mechanisms

Part of the difficulty many of the African LDCs have had in engaging with offset projects has been related to the bureaucracy that surrounds the authorization of projects and the eventual issuing of credits. Within the CDM, an elaborate system of checks and balances under the CDM Executive Board means that the overall rate of project authorization and implementation has been slow.

A second reason that African nations have had low success rates of engaging with the CDM and forest offset projects is that neither energy-based projects nor afforestation/reforestation projects, the two mainstays of these mechanisms, have attracted many foreign investors (Sieghart, 2009). Even though there may be high technical potential for projects, barriers persist (de Gouvello et al., 2008). As remote-sensing capabilities have improved our ability to accurately monitor forest stocks (Gibbs et al., 2007), the post-Kyoto agreement may consider country-wide forest stocks under REDD, making individual projects less important in the future (Minang et al., 2008). However, some of the same challenges that affected CDM afforestation or reforestation projects in Africa may apply to REDD. These issues include tree plantation projects that are essentially designed to serve as “carbon farms”, without offering significant local benefits (Ringius, 2002), land rights barriers (Unruh, 2008), and the issues of ongoing deforestation pressures or loss of carbon through fires, which may deter investors (Murdiyarso et al., 2008).

A1.1.3 Soil carbon and offsets

Interest around the potential for integrating soil carbon sequestration into the CDM has existed since its inception, but soil carbon enhancement projects under the CDM and other offset mechanisms are currently limited. Although there is an established methodology for assessing soil organic carbon (UNFCCC, 2008) under afforestation/reforestation projects, current regulations allow for soil carbon pools to be neglected in many cases (UNFCCC, 2006), and there are currently no CDM projects that focus primarily on soil carbon. This is lamentable, because the agricultural co-benefits of increasing soil carbon are manifold and such projects have strong potential to provide true sustainable development. Mechanisms such as conservation tillage, slowing land conversion, reducing erosion, or management of organic residues can all contribute to the reduction of GHG emissions while promoting soil health and thereby supporting local communities (Lal, 2004). However, delivering inexpensive and credible proof of soil carbon increases is not without challenges (Paustian et al., 2009). A second issue is that, similar to tree-planting projects, some gains could be reversed upon a shift back to old cultivation practices, undoing the carbon storage that had occurred and been credited. Recently, an opportunity has emerged that has the potential to overcome some of these roadblocks for soil carbon: biochar.

Biochar is a highly stable carbon compound created when biomass is heated to temperatures between 350 and 600°C in the absence of oxygen. Biochar was most notably identified in ancient soils of the Amazon, known as *Terra preta*, where these dark, carbon-rich soils have remarkably high agricultural productivity in an area of generally nutrient-poor soils (Lehmann, 2007). Thought to be created by pre-Columbian populations, these soils are notable today not only for their high fertility, but also for the stability of their carbon – carbon in these soils has been identified to be over 3000 years old (Glaser et al., 2001). Modern-day interests in enhancing soil health, organic agriculture, and sequestering carbon have led to a resurgence of interest in biochar (Lehmann and Joseph, 2009).

Today, biochar may be produced by a variety of methods, from small cook stove systems to larger bioenergy systems. In Africa, one of the the most likely options for biochar offset projects may be the introduction of biochar-producing stoves. Traditional biomass would be used to produce energy for cooking, with biochar remaining as a co-product, which could then be applied to soils (Figure A1.1.2). Farmers could benefit from increased crop yields (Kimetu et al., 2008). If these stoves are more efficient and cleaner-burning than conventional stoves, as shown for improved combustion stoves (Johnson et al., 2009), they could significantly reduce fuel gathering pressure and respiratory diseases (Bruce et al., 2002). Such biochar has been found to have mean residence times in excess of 1000 years (Lehmann and Joseph, 2009), which means that there is a greater net GHG reduction benefit when biochar is sequestered in soil, rather than being burnt (Gaunt and Lehmann, 2008).

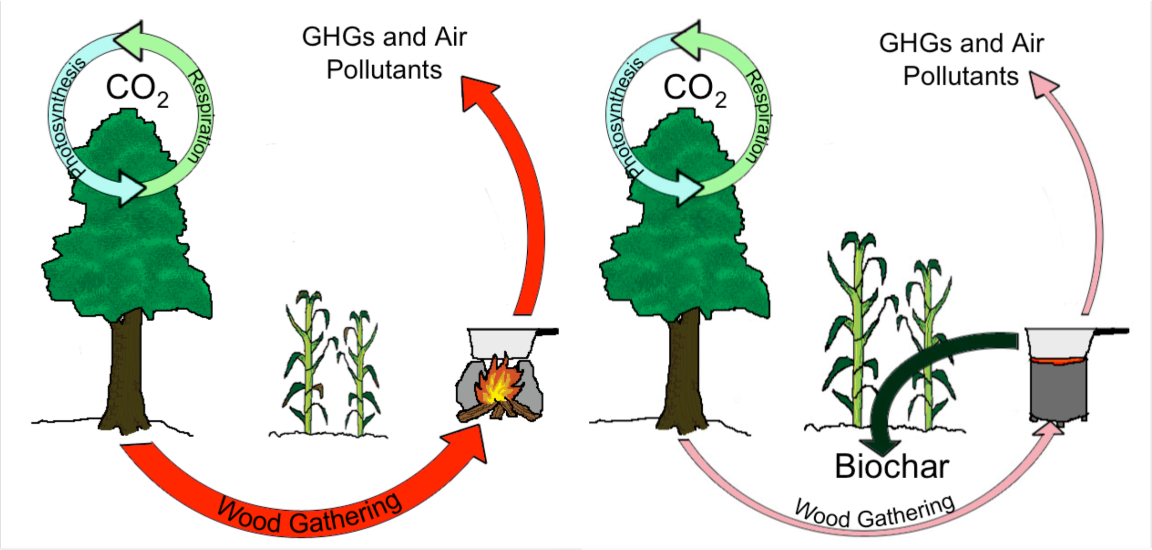

Figure A1.1.2. Greenhouse gas flows in a traditional cook stove system (left) as compared to a biochar cook stove system (right)

With biochar mentioned as a mitigation strategy in the current UNFCCC (2009b) negotiating text for the pending international climate agreement, it is crucial to begin to critically assess biochar as a piece of the international emissions reduction system. Biochar could have real potential to be Africa's key to initiate an engagement with international offset projects and to support soil carbon management as a valuable mechanism for carbon sequestration and soil health improvement. Many of the serious pitfalls discussed earlier are avoided in a biochar system: its application to soil could directly contribute to local sustainable development, by enhancing soil organic carbon, improving nutrient retention, and increasing crop yields (Lehmann et al., 2006). Furthermore, its production in a bioenergy system could use alternative feedstocks, such as crop residues, forest leaf litter or grasses (Yaman, 2004), potentially reducing deforestation pressures. Under this bioenergy system, carbon credits could be earned both from the provision of cleaner energy or fuels to local people as shown for combustion stoves (Johnson et al., 2009) and also from the sequestration of carbon from the addition of the resulting biochar to soil (Lehmann et al., 2006). This sequestration would be secure. The amount of biochar applied to soil can be quantified on a mass basis, and it is identifiable or traceable (Lehmann and Joseph, 2009). Even years later, it would be possible to determine how much of the applied biochar remains in the soil and the biochar would not be at risk of loss due to fire or changed management regimes (Lehmann, 2007). The important issue of additionality is relatively easily addressed: biochar production and application is not currently practiced in agricultural systems, so such a shift in practice would clearly be a deviation from "business as usual".

Although it has significant soil health benefits beyond carbon sequestration, initial development and a start to widespread implementation of biochar technologies would require financing through a mechanism such as the CDM. The technical potential for such an approach is high. If biochar-producing cook stove projects were applied to 50% of current household fuel wood burning in Africa (Yevich and Logan, 2003), this could potentially sequester over 100 Mt of CO_2 annually as biochar, creating over 100M CERs from the biochar C sequestration alone[5]. At a price of $13.6 per CER (mean for 2008: Capoor and Ambrosi, 2008), this would be worth around $1.5Bn per year. While, being realistic, it is unfortunately likely that this money would never reach those African communities where projects are being implemented, local communities would still benefit. Biochar-producing stoves have strong sustainability linkages to enhanced soil fertility (Lehmann, 2007) and to improved respiratory health due to reduced emissions of particulates, if they are developed as successfully as improved combustion stoves (Johnson et al., 2009).

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[5] Assuming a wood carbon content of 50% by mass, conversion factor for carbon in fuelwood converted into stable biochar carbon of 40%, and at least equivalent fuel use (as proven for non-pyrolysis improved cookstoves by Johnson et al., 2008), thereby not requiring an increase in fuel use. Note that if the reduction in fuel use were great, then total reduction potential might be lower depending on the fate of the now non-harvested wood.

Initially, it seems that the potential for such projects could be large, but rapid and extensive field research must be done in advance of significant implementation of biochar as an offset. Rigorous inquiry is also required into those questions behind any offset strategy – is it really appropriate to justify financing emissions reductions in the global south in order to continue to emit GHGs in the global north when the stakes are as high as those we currently face with global climate change? Although improved stoves in general may provide efficiency increases, resulting in decreases in fuel use, attempts to justify credits for reductions in deforestation may be spurious, if the wood left ungathered as a result of stove introduction is simply made available for another use (resulting in "leakage"). This is one reason the production of biochar and its application to soils is particularly appealing – because of the certainty of its sequestration, regardless of the effects of reduced fuel wood use. The land-use change issues associated with any significant biofuel use (*e.g.*, Fargione et al., 2008) would be somewhat bypassed in a stove system, as long as biomass use is limited by the amount of food that is needed for cooking, and not by the amount of biomass that can be accessed.

A1.1.4 Conclusions and recommendations

Interest is growing regarding a full evaluation of biochar's potential for mitigation of climate change – a group of eleven African nations and the UN Convention to Combat Desertification (UNCCD) have both submitted papers proposing biochar as an item to be considered during the next rounds of UN climate negotiations (African Governments, 2009; UNCCD, 2009). Our global food system depends on the sustainable management of agricultural soils and biochar could very well be Africa's key to the doors that the CDM was supposed to open toward sustainable development and climate change mitigation. Significant field-level research is needed first, but biochar could lead the way for other soil carbon management strategies to improve soil health and provide tangible local benefits while addressing global warming, making it a strong candidate for future incarnations of the CDM and other offset mechanisms in Africa.

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APPENDIX 1.2

SUPPLEMENTARY PAPER: SYSTEMATIC UNDER- AND OVERESTIMATION OF GHG REDUCTIONS IN RENEWABLE BIOMASS SYSTEMS[6]

Abstract

This paper identifies a critical systematic error in greenhouse gas accounting in renewable biomass systems. While CO_2 emissions from renewable biomass energy systems are generally considered to have a net impact of 0, no similar adjustment is made for carbon-based products of incomplete combustion, such as methane, in renewable systems. This results in an under- or overestimation of the impact of CH_4 by 12.3% and CO by ~478% in renewable systems. This error is propagated both in scientific studies and in carbon accounting policies. We advocate first for full-carbon accounting of biomass-derived emissions, but also provide adjusted global warming impacts for emissions from proven renewable systems.

A1.2.1 Addressing the assumptions of "carbon neutrality"

Current research on and methodologies for biofuel-based carbon accounting perpetuate a systematic error: the misapplication of the concept of "carbon neutrality." While the fact that this concept has been applied inappropriately has been identified (Searchinger et al. 2009), we have noticed an important new error being perpetuated when accounting for the carbon (C)-based non-CO_2 greenhouse gas (GHG) emissions of renewable biomass fuel systems. The crux of the error is that in truly renewable biomass systems, the emission of C-based products of incomplete combustion (PICs),

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[6] Submitted and revised for *Climatic Change Letters* under Whitman, T.; Lehmann, J..

such as methane (CH_4), would result in a lower net GHG impact than under non-renewable conditions (Deluchi 1991; Varshney and Attri 1999), a fact which is consistently overlooked in C accounting methodologies, resulting in the under- and overestimation of GHG reductions in systems that rely on renewable biomass for fuel.

At present, the carbon neutral status of biofuels is often justified by the assumption that CO_2 emitted from the combustion of biomass fuels was recently removed from the atmospheric CO_2 stocks by plants fixing C, and thus should not be counted as a net GHG emission (e.g., Roedl 2010). This assumption can be problematic for many reasons (Friedland and Gillingham 2010; Johnson 2009; Pingoud et al. 2010; Searchinger et al. 2009). One of the foremost accounting problems occurs when the removal of biomass from some systems, though it may grow back eventually, actually results in lower net C storage over time than would have occurred under the baseline scenario with no harvesting of biomass (Searchinger 2010). When this is properly accounted for and avoided, we can consider the C in biomass to be truly "additional" (Searchinger 2010). Other sources may use the term "renewable" for this biomass C. We will use this term, because it is consistent with the literature in which the error discussed in this paper is most striking – biomass cook stove literature – but we recognize that "additional" may be a more appropriate term. (We discuss the conditions for the application of this term in more depth in Section 3.)

Carbon accounting for non-CO_2 GHGs has also been problematic. When combustion of fuels is not completely efficient, it produces some carbon-based PICs besides CO_2, such as CH_4, which can have higher global warming impacts than CO_2. While the carbon neutral biofuel paradigm does not count CO_2 from renewable biofuel sources, in some cases, these non-CO_2 gases are counted directly as net GHG emissions (Caserini et al. 2010; Cherubini 2010; Gold Standard 2010; IPCC 2006; UNFCCC 2007). While this is relatively sensible for non-C-based GHGs, such as

N_2O, and is an improvement over ignoring all GHG emissions from "renewable" biomass, for C-based GHGs, it is problematic, as we discuss below.

A1.2.2 The consequences of ignoring C stoichiometry

The best way to understand this error is by considering a system in which completely renewable biomass is combusted. Under perfectly efficient combustion (Figure 1.A), each CO_2 molecule released through burning the biomass was originally fixed from atmospheric CO_2 through photosynthesis and will be taken up again as the biomass re-grows, resulting in zero net emissions. The net change in the CO_2 stock in the atmosphere is 0. Under the alternate scenario (Figure 1.B), combustion is not perfectly efficient, and some of the C from the CO_2 that was fixed is released upon combustion not as CO_2, but as CH_4. This CH_4 has a warming effect equivalent to 25 times an equivalent mass of CO_2, based on the IPCC's 100-year global warming potential (GWP) (Forster et al. 2007). On a molar basis, rather than the standard mass basis, the warming effect of CH_4 is equivalent to 9.1 times that of CO_2. Under the renewable biomass C neutrality paradigm, we would be inclined to suggest that the net impact of this system is 9.1 mol CO_2-equivalents (CO_2e), because we ignore CO_2 emissions but count all non-CO_2 GHG emissions in a renewable system. However, because CH_4 is a C-based PIC, the emission of one molecule of CH_4 means that one atom of C will not be released as CO_2. If the system is, indeed, renewable, as we have stipulated, then a CO_2 molecule will still be fixed to replace the atom of C released from the plant. Thus, the net impact, or "renewable GWP" (rGWP) of this system is actually $9.1 – 1 = 8.1$ mol CO_2e. Ignoring the biogeochemistry of the system by thinking of "methane gas" and not remembering that this stands for the C-containing chemical compound CH_4, the stoichiometry of the system is lost, and its GHG impact will be overestimated.

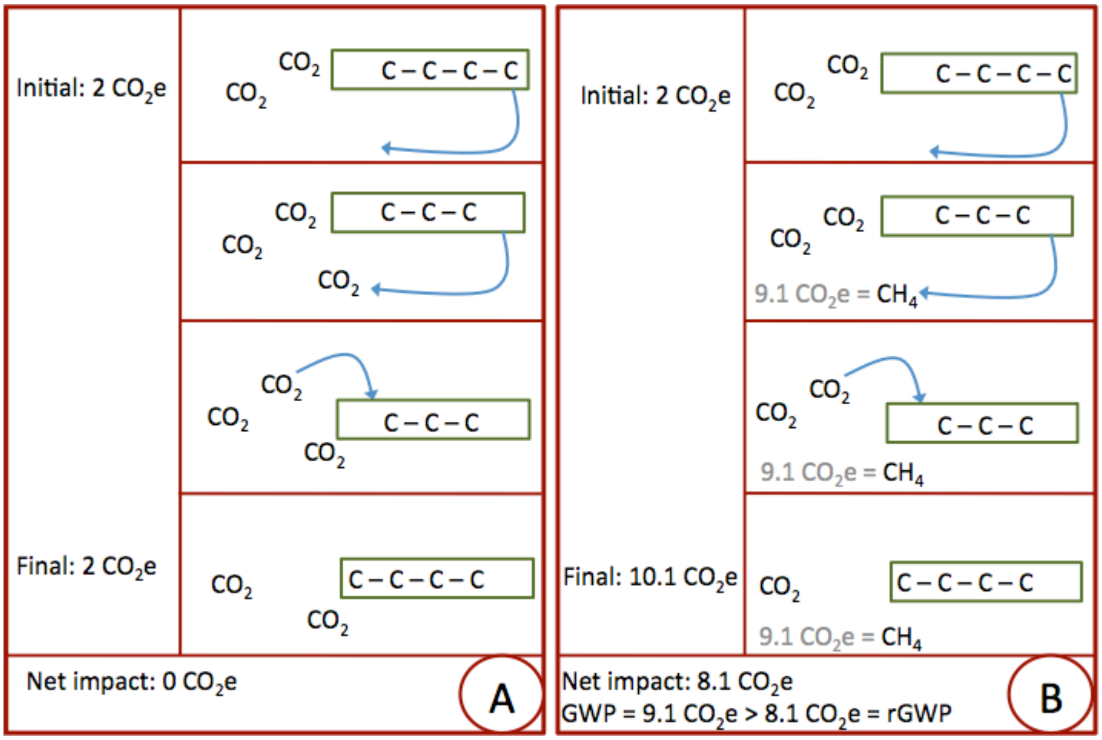

Figure A1.2.1. Simplified model of C flows in a renewable biomass-burning system, demonstrating "renewable GWP" (rGWP) for CH_4 in CO_2 equivalents (CO_2e). Free molecules represent gases, boxed C atoms represent biomass, and arrows represent net carbon fixation through photosynthesis and carbon loss through burning. Scenario A depicts a completely efficient burn, where all C is released as CO_2, while scenario B depicts an inefficient burn, where C is released as CH_4. In scenario B, much of the burn would be released as CO_2, but the focus here is on the net effect of one CH_4 molecule.

The magnitude of this error depends heavily on the GWP of the gases under consideration. Although methane is the only C-based non-CO_2 GHG currently counted under the Kyoto protocol that would be produced through combustion (HFCs and PFCs contain carbon and are counted, but would not be significant PICs), other PICs are known to have warming effects, such as non-methane hydrocarbons or carbon monoxide (CO), which enhances ozone and reduces OH levels, leading to greater CH_4 concentrations (Forster et al. 2007). For compounds with high GWPs, the overestimation makes only a small difference, but for compounds with low GWPs, it results in a very large error (Figure 2). For example, in systems where all biomass burning is renewable, the estimated total GHG impact for CH_4 without the renewability correction factor would be 12.3% greater than its true value. If the warming impact of CO, which is estimated to lie around 1.9 by mass (Forster et al. 2007), or 1.2 on a molar basis, is considered, the estimated total GHG impact for CO from renewable sources without the renewability correction factor would be 478% greater than its true value.

The degree to which this error affects the final estimation of a system's impact scales directly with the fraction of the total system emissions made up by non-CO_2 C-based GHG emissions from renewable biomass. In very clean-burning industrial systems, CH_4 emissions are often relatively low compared to CO_2 – the IPCC default CH_4 emission factor for stationary combustion of solid biomass is 0.03% that of CO_2 by mass (IPCC 2006). However, for biomass cook stoves, this ratio may be two to three orders of magnitude higher (Johnson et al. 2008; Smith et al 1993). In the system studied by Johnson et al (2008), where 80% of biomass gathering is renewable, the GHG emission reductions achieved through the introduction of improved cook stoves are around 30% higher than they would be if applying the rGWP correction factor. While other uncertainties around the impact of cook stove emissions may be substantial in comparison to this error – for example, the impact of particulate black carbon on climate change is poorly understood (Bond and Sun 2005) – this is no excuse to continue to use improper accounting procedures.

It is important to recognize that this error can result in an underestimation or an overestimation of GHG impact, depending on the project scenario and the baseline scenario. Overestimation occurs whenever the project scenario provides a reduction of non-CO_2 C-based GHG emissions from renewable biomass sources from that which

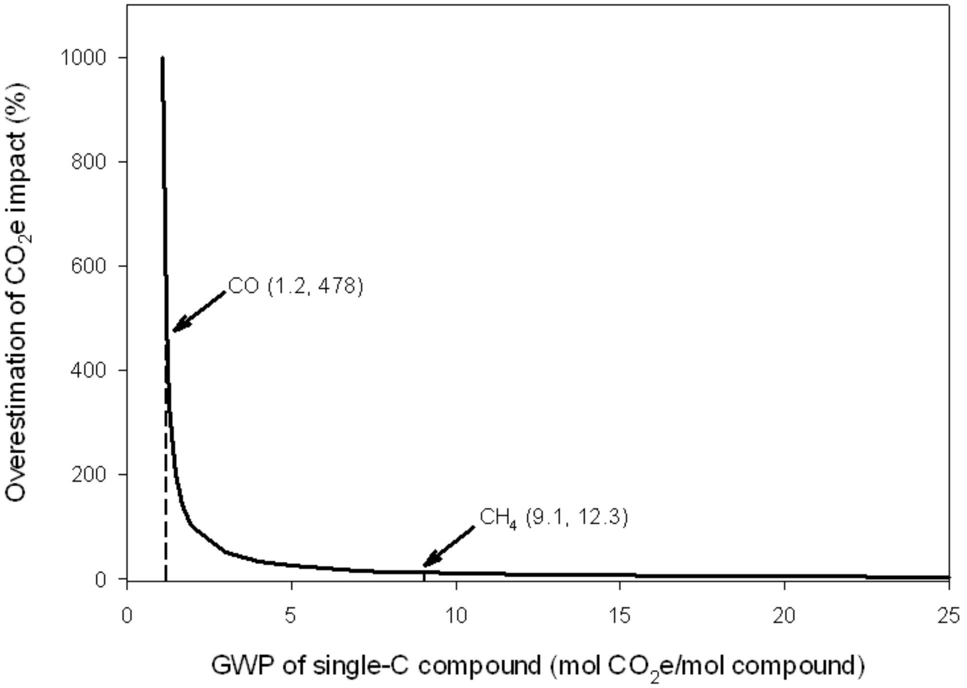

Figure A1.2.2. Percent overestimation of global warming impact vs. molar GWP of single-C GHGs

was being used under the baseline scenario. An example would be if a cook stove using renewable biomass were improved to require less fuel. However, if the project scenario represents a switch to renewable biomass sources from non-renewable biomass or fossil fuel sources, then this error would cause its potential reductions to be underestimated. For example, if the baseline scenario were fossil fuel burning (all fuel non-renewable) and the project scenario were renewable biomass combustion, then counting uncorrected CH_4 emissions from the biomass combustion would maintain a conservative estimate of emission reductions. If the goal were simply to measure the total emissions of a system, then counting uncorrected CH_4 emissions from the biomass combustion would also result in a higher estimate of total emissions, which would be conservative. In general, an underestimation will result if net emissions from renewable biomass sources increase under the project scenario (although total project emissions may decrease), while a net decrease in emissions from renewable biomass sources results in an overestimation.

A1.2.3 Righting two wrongs: addressing two carbon accounting issues

Whether this error in accounting for CH_4 and similar PICs is problematic or not depends partially on how CO_2 emissions are accounted for in the first place. We consider here three dominant approaches: (i) CO_2 emissions from biomass fuels are given a GHG impact value of 0, (ii) only a portion of CO_2 emissions from biomass fuels are counted, dependent on what portion of the biomass is from non-renewable sources, (iii) all CO_2 emissions are counted and all changes in biomass C storage over time are also counted. We will not discuss the specific merits or drawbacks of each approach in detail here, but rather, focus on how the treatment of CO_2 emissions affects the PIC accounting error (as summarized in Table 1).

In the case of the first approach, if it is deemed justifiable to ignore emissions of CO_2, and if CH_4 is considered to be a significant source of emissions (it may not be counted at all [Roedl 2010]), then the same justification for ignoring CO_2 emissions should be applied for using the rGWP or a similar accounting approach for CH_4 emissions. This approach has been used by some (DeLuchi 1991; Sander and Murthy 2010) but is still not applied by others (Caserini et al. 2010; Cherubini 2010; UNFCCC 2007; Gadde et al. 2009). However, as discussed in Section 2, depending on the baseline scenario, this can result in conservative emission reductions (e.g., UNFCCC 2007), in which case it is less critical that the error be righted.

The second approach begins to recognize that in many systems, particularly for wood fuel gathering, biomass comes from different sources with different degrees of renewability. This approach is currently being used in small-scale biomass fuel applications, particularly cook stove research (Johnson et al. 2009; MacCarty et al. 2008), the Kyoto Protocol's Clean Development Mechanism (CDM)'s small-scale methodology (UNFCCC 2009) and the Gold Standard's carbon offset methodology for improved cook stoves (Gold Standard 2010). It combines the carbon neutrality paradigm with estimates of the degree of renewability of the biomass used for fuel (Johnson et al. 2010a).

A measure of the fraction of fuel that is from "non-renewable" biomass (fNRB) is used to determine the fraction of CO_2 emissions that should be counted as net emissions, while remaining, "renewable" CO_2 emissions are ignored. In order for this principle to function appropriately, if any biomass designated as "renewable" is gathered from a stock in perpetuity, the stock should both be replenished, and also not have increased beyond its stable level if the gathering were not to have taken place (i.e., be truly "additional" biomass [Searchinger 2010]). If biomass designated as "non-renewable" is gathered from a stock, it should immediately deplete the stock, and the stock should never be replenished. However, these extreme scenarios do not usually apply neatly to a given region, so certain conventions are used to estimate fNRB.

Projects under the CDM consider NRB to be biomass that is not demonstrably renewable and meets at least two out of three other conditions. Demonstrably renewable biomass is defined for forests as cases where: (i) the land area remains a forest, (ii) sustainable management ensures C stocks do not decrease over time, although they may temporarily decrease due to harvesting, (iii) locally applicable forestry and nature conservation regulations are complied with. In addition to not being demonstrably renewable biomass, the three conditions to designate non-renewable biomass are: (i) users spend increasing time or travel increasing distances to gather or transport wood into the project area, (ii) data show that C stocks are being depleted in the project area, (iii) fuel wood price is increasing (UNFCCC 2009).

In these cases where biomass is classified as being renewable or non-renewable, non-CO_2 GHG emissions are not treated consistently. The CDM cook stove approach does not consider any emissions from renewable biomass (UNFCCC 2009), while others consider the non-CO_2 emissions from both renewable and non-renewable biomass sources (Gold Standard 2010; Johnson et al. 2009; MacCarty et al. 2008; *Chapter 2*). For non-renewable fuel emissions, CH_4 emissions are weighted by their full GWP and there is no error. However, when renewable fuel emissions are counted, CH_4 emissions should be valued according to the rGWP wherever CO_2 emissions are ignored. The CDM's current methodology remains conservative, because it does not include emissions from any renewable biomass (UNFCCC 2009), but the Gold Standard cook stove methodology and other studies currently overestimate any emission reductions from renewable biomass sources (Gold Standard 2010; Johnson et al. 2008; MacCarty et al. 2008).

Both these first two approaches rely on assumptions about the renewability status of the system. Perhaps the most robust way of addressing such an error is the third approach – to apply full carbon accounting techniques, where the net flows of carbon are explicitly traced over time, including the CO_2 and non-CO_2 emissions from using bioenergy as well as the increases or decreases in net fixation of CO_2 by biological carbon stock due to land-use changes (González-García et al. 2010; Guinée et al. 2009; Johnson 2009; Searchinger et al. 2009). If a biofuel is truly carbon-neutral, then this fact will emanate from the C balance sheet and there is no need to treat CH_4 emissions differently. This system-based solution is an ideal approach for scientific certainty, and can be applied at the project scale by measuring or modelling biomass growth and fuel emissions (Bailis 2009).

Table A1.2.1. Accounting approaches for CO_2 emissions and C-based non-CO_2 GHG emissions (e.g., CH_4) in biomass fuel systems

Current accounting for CO_2 emissions	**Current and recommended accounting for non-CO_2 C-based GHG emissions**
CO_2 emissions are given a value of 0 because biomass stocks are determined to be "renewable" or "additional".	C-based non-CO_2 GHG emissions are not included (Roedl 2010) or are included and weighted either using the full GWP (Caserini et al. 2010; Cherubini 2010; Gadde et al. 2009) or the rGWP (DeLuchi 1991; Sander and Murthy 2010).
	If PIC impacts are included (and CO_2 neutrality is justified), rGWP should be applied, particularly where this results in a conservative estimate of emission reductions.
CO_2 emissions are partly counted (non-renewable biomass) and partly valued at 0 (renewable biomass), depending on fNRB of biomass fuel.	C-based non-CO_2 GHG emissions from non-renewable biomass are included in all cases. Emissions from renewable biomass are excluded (UNFCCC 2009) or included with full GWP weighting (MacCarty et al. 2008; Johnson et al. 2009; Gold Standard 2010) or included with a reduced GWP (*Chapter 2*).
	The impact of PIC emissions from renewable biomass should be weighted using the rGWP, particularly where this results in a conservative estimate of emission reductions.
All C flows within the system are modeled explicitly over time.	The issue of miscounting non-CO_2 C-based GHGs is avoided by modeling the C fixation by plants directly (Bailis 2009; González-Garía et al. 2010).

A1.2.4 Addressing the carbon accounting error

Substantially different approaches are being used in order to determine the C budget of renewable biomass fuel systems, with varying consequences. As discussed above, the optimal approach to avoid many C accounting errors and increase confidence in the C accounting for offsets or national inventories would be to use full-system carbon accounting, by explicitly modeling or measuring biomass and soil C growth, decay, and loss as well as emissions.

If renewability status or the fNRB can be justified and are used, however, the proposed rGWP corrections must be applied in place of GWPs for PICs from renewable biomass in order to correct this error (Table 2). (See Shine [2010] for a critique of GWPs and Levassueur et al. [2010] for a discussion for applying GWPs to measure the impacts of gases emitted over time.)

Table A1.2.2. 100-year global warming potential (GWP) (Forster et al. 2007) and renewable biomass global warming potential (rGWP) on a mass and molar basis

Compound	**GWP (t CO_2e/ t GHG)**	**rGWP (t CO_2e/ t GHG)**	**GWP (mol CO_2e/ mol GHG)**	**rGWP (mol CO_2e/ mol GHG)**
CH_4	25	22.26	9.12	8.12
CO	1.9	0.33	1.21	0.21

To avoid underestimating PIC emission impacts, the rGWP should only be used where biomass can be explicitly proven to be renewable or where applying the correction results in a conservative estimate of emission reductions, such as in improved biomass cook stove systems. This recommendation should be added to those discussed by Johnson et al. (2010a, 2010b) for revising the current accounting procedures for biomass cook stove systems, and to those recommended by Searchinger et al. (2009) for improving GHG inventories.

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APPENDIX 2.1

PRIMARY DATA FOR CHAPTER ONE

Data includes hazelnut chars, which were not considered for analysis because %C measurements had very wide errors, likely due to challenges of adequately homogenizing the original materials and the BCs.

Table A2.1.1 %C in original BCs and uncharred materials

Feedstock	Temperature (°C)	%C first analysis	%C second analysis (Binh)	%C third analysis (Thea)
Bull w/ sawdust	60	43.70	43.93	
Bull w/ sawdust	300	61.05	58.02	
Bull w/ sawdust	350	63.42	61.55	
Bull w/ sawdust	400	68.28	68.79	
Bull w/ sawdust	450	72.15	69.38	
Bull w/ sawdust	500	65.62	71.66	
Bull w/ sawdust	550	72.71	72.03	
Bull w/ sawdust	600		74.44	75.59
Corn Stalks	60	41.64	43.60	
Corn Stalks	300	59.57	57.98	
Corn Stalks	350	60.42	60.40	
Corn Stalks	400	62.61	62.57	
Corn Stalks	450	67.67	66.94	
Corn Stalks	500	67.98	70.21	
Corn Stalks	550	68.12	72.78	
Corn Stalks	600	71.99	67.99	
Dairy w/ Rice Hulls	60	43.10	43.11	
Dairy w/ Rice Hulls	300	62.14	60.42	
Dairy w/ Rice Hulls	350	64.74	62.86	
Dairy w/ Rice Hulls	400	68.27	65.95	
Dairy w/ Rice Hulls	450	71.17	68.97	
Dairy w/ Rice Hulls	500	71.53	69.90	
Dairy w/ Rice Hulls	550	72.34	72.35	
Dairy w/ Rice Hulls	600	72.57	72.23	
Hazelnuts	60	45.06	46.98	
Hazelnuts	300	70.16	69.59	
Hazelnuts	350	71.12	71.52	
Hazelnuts	400	76.56	74.96	
Hazelnuts	450	78.95	77.97	
Hazelnuts	500	80.56	79.54	
Hazelnuts	550	82.39	85.48	
Hazelnuts	600	85.40	82.81	
Oak	60	45.88	48.23	
Oak	300	67.34	60.52	
Oak	350	76.37	73.48	
Oak	400	80.47	75.31	
Oak	450	88.71	81.40	
Oak	500	87.12	80.70	
Oak	550	90.28	85.26	
Oak	600	90.21	84.96	

Table A2.1.1 (Continued)

Pine	60	45.20	45.35	
Pine	300	63.24	60.98	
Pine	350	69.50	70.06	
Pine	400	73.20	75.65	
Pine	450	81.25	79.63	
Pine	500	85.11	81.67	
Pine	550	84.54	85.77	
Pine	600	86.26	87.67	
Poultry w/ sawdust	60	24.52	24.74	
Poultry w/ sawdust	300			29.38
Poultry w/ sawdust	350		27.88	24.32
Poultry w/ sawdust	400		21.43	20.67
Poultry w/ sawdust	450		17.97	19.83
Poultry w/ sawdust	500		23.00	24.97
Poultry w/ sawdust	550		19.84	21.11
Poultry w/ sawdust	600		18.50	22.40

Table A2.1.2 Jar component masses for 5 month incubation

Jar #	Feedstock	Temperature (°C)	Sand mass (g)	Char mass (g)
300	Hazelnuts	60	19.2	0.8
301	Hazelnuts	60	19.2	0.8
302	Hazelnuts	60	19.202	0.801
303	Hazelnuts	60	19.201	0.802
304	Hazelnuts	300	19.2	0.802
305	Hazelnuts	300	19.2	0.802
306	Hazelnuts	300	19.2	0.801
307	Hazelnuts	300	19.201	0.802
308	Hazelnuts	350	19.2	0.802
309	Hazelnuts	350	19.202	0.801
310	Hazelnuts	350	19.201	0.801
311	Hazelnuts	350	19.201	0.8
312	Hazelnuts	400	19.2	0.801
313	Hazelnuts	400	19.202	0.801
314	Hazelnuts	400	19.202	0.8
315	Hazelnuts	400	19.202	0.802
316	Hazelnuts	450	19.201	0.8
317	Hazelnuts	450	19.201	0.802
318	Hazelnuts	450	19.201	0.8
319	Hazelnuts	450	19.2	0.802
320	Hazelnuts	500	19.2	0.8
321	Hazelnuts	500	19.201	0.8
322	Hazelnuts	500	19.201	0.8
323	Hazelnuts	500	19.202	0.8
324	Hazelnuts	550	19.2	0.801
325	Hazelnuts	550	19.2	0.8
326	Hazelnuts	550	19.202	0.801
327	Hazelnuts	550	19.202	0.8
328	Hazelnuts	600	19.202	0.802
329	Hazelnuts	600	19.201	0.802
330	Hazelnuts	600	19.201	0.802
331	Hazelnuts	600	19.202	0.8
332	Pine	60	19.202	0.801
333	Pine	60	19.202	0.8
334	Pine	60	19.2	0.8
335	Pine	60	19.2	0.8
336	Pine	300	19.2	0.8
337	Pine	300	19.201	0.802
338	Pine	300	19.201	0.802
339	Pine	300	19.2	0.8
340	Pine	350	19.202	0.8
341	Pine	350	19.201	0.801

Table A2.1.2 (Continued)

342	Pine	350	19.201	0.8
343	Pine	350	19.2	0.802
344	Pine	400	19.201	0.8
345	Pine	400	19.201	0.801
346	Pine	400	19.2	0.8
347	Pine	400	19.201	0.801
348	Pine	450	19.2	0.8
349	Pine	450	19.2	0.801
350	Pine	450	19.202	0.8
351	Pine	450	19.201	0.802
352	Pine	500	19.2	0.801
353	Pine	500	19.202	0.801
354	Pine	500	19.201	0.8
355	Pine	500	19.202	0.8
356	Pine	550	19.201	0.8
357	Pine	550	19.201	0.8
358	Pine	550	19.2	0.8
359	Pine	550	19.2	0.8
360	Pine	600	19.202	0.8
361	Pine	600	19.201	0.802
362	Pine	600	19.201	0.802
363	Pine	600	19.202	0.802
364	Oak	60	19.202	0.8
365	Oak	60	19.201	0.801
366	Oak	60	19.201	0.8
367	Oak	60	19.201	0.8
368	Oak	300	19.202	0.8
369	Oak	300	19.201	0.802
370	Oak	300	19.201	0.8
371	Oak	300	19.2	0.8
372	Oak	350	19.202	0.8
373	Oak	350	19.2	0.801
374	Oak	350	19.202	0.802
375	Oak	350	19.202	0.8
376	Oak	400	19.201	0.801
377	Oak	400	19.2	0.8
378	Oak	400	19.202	0.8
379	Oak	400	19.201	0.8
380	Oak	450	19.2	0.801
381	Oak	450	19.202	0.801
382	Oak	450	19.202	0.8
383	Oak	450	19.2	0.801
384	Oak	500	19.201	0.802
385	Oak	500	19.2	0.8
386	Oak	500	19.2	0.802
387	Oak	500	19.201	0.802

Table A2.1.2 (Continued)

388	Oak	550	19.202	0.8
389	Oak	550	19.2	0.801
390	Oak	550	19.2	0.8
391	Oak	550	19.2	0.8
392	Oak	600	19.2	0.8
393	Oak	600	19.201	0.8
394	Oak	600	19.2	0.801
395	Oak	600	19.201	0.8
396	Poultry w/ sawdust	60	19.201	0.801
397	Poultry w/ sawdust	60	19.201	0.801
398	Poultry w/ sawdust	60	19.201	0.801
399	Poultry w/ sawdust	60	19.201	0.801
400	Poultry w/ sawdust	300	19.202	0.802
401	Poultry w/ sawdust	300	19.201	0.802
402	Poultry w/ sawdust	300	19.201	0.801
403	Poultry w/ sawdust	300	19.2	0.802
404	Poultry w/ sawdust	350	19.201	0.802
405	Poultry w/ sawdust	350	19.201	0.8
406	Poultry w/ sawdust	350	19.2	0.8
407	Poultry w/ sawdust	350	19.201	0.801
408	Poultry w/ sawdust	400	19.201	0.801
409	Poultry w/ sawdust	400	19.201	0.8
410	Poultry w/ sawdust	400	19.202	0.801
411	Poultry w/ sawdust	400	19.2	0.802
412	Poultry w/ sawdust	450	19.2	0.8
413	Poultry w/ sawdust	450	19.202	0.801
414	Poultry w/ sawdust	450	19.201	0.802
415	Poultry w/ sawdust	450	19.201	0.8
416	Poultry w/ sawdust	500	19.201	0.801
417	Poultry w/ sawdust	500	19.2	0.801
418	Poultry w/ sawdust	500	19.202	0.801
419	Poultry w/ sawdust	500	19.202	0.802
420	Poultry w/ sawdust	550	19.201	0.802
421	Poultry w/ sawdust	550	19.201	0.8
422	Poultry w/ sawdust	550	19.2	0.8
423	Poultry w/ sawdust	550	19.201	0.8
424	Poultry w/ sawdust	600	19.201	0.801
425	Poultry w/ sawdust	600	19.2	0.802
426	Poultry w/ sawdust	600	19.2	0.801
427	Poultry w/ sawdust	600	19.2	0.802
428	Corn stalks	60	19.201	0.801
429	Corn stalks	60	19.2	0.8
430	Corn stalks	60	19.2	0.801
431	Corn stalks	60	19.202	0.801
432	Corn stalks	300	19.2	0.8
433	Corn stalks	300	19.201	0.8
434	Corn stalks	300	19.201	0.802

Table A2.1.2 (Continued)

435	Corn stalks	300	19.201	0.8
436	Corn stalks	350	19.2	0.801
437	Corn stalks	350	19.202	0.801
438	Corn stalks	350	19.202	0.801
439	Corn stalks	350	19.202	0.8
440	Corn stalks	400	19.202	0.801
441	Corn stalks	400	19.202	0.802
442	Corn stalks	400	19.2	0.8
443	Corn stalks	400	19.202	0.801
444	Corn stalks	450	19.202	0.8
445	Corn stalks	450	19.202	0.802
446	Corn stalks	450	19.202	0.801
447	Corn stalks	450	19.201	0.8
448	Corn stalks	500	19.202	0.8
449	Corn stalks	500	19.202	0.801
450	Corn stalks	500	19.202	0.8
451	Corn stalks	500	19.201	0.801
452	Corn stalks	550	19.2	0.801
453	Corn stalks	550	19.201	0.802
454	Corn stalks	550	19.201	0.8
455	Corn stalks	550	19.201	0.801
456	Corn stalks	600	19.202	0.802
457	Corn stalks	600	19.202	0.801
458	Corn stalks	600	19.2	0.8
459	Corn stalks	600	19.202	0.801
460	Dairy w/ rice hulls	60	19.2	0.802
461	Dairy w/ rice hulls	60	19.202	0.802
462	Dairy w/ rice hulls	60	19.202	0.8
463	Dairy w/ rice hulls	60	19.202	0.8
464	Dairy w/ rice hulls	300	19.201	0.802
465	Dairy w/ rice hulls	300	19.201	0.802
466	Dairy w/ rice hulls	300	19.2	0.8
467	Dairy w/ rice hulls	300	19.202	0.8
468	Dairy w/ rice hulls	350	19.201	0.8
469	Dairy w/ rice hulls	350	19.2	0.8
470	Dairy w/ rice hulls	350	19.2	0.801
471	Dairy w/ rice hulls	350	19.201	0.8
472	Dairy w/ rice hulls	400	19.201	0.802
473	Dairy w/ rice hulls	400	19.202	0.802
474	Dairy w/ rice hulls	400	19.201	0.8
475	Dairy w/ rice hulls	400	19.201	0.802
476	Dairy w/ rice hulls	450	19.202	0.802
477	Dairy w/ rice hulls	450	19.2	0.802
478	Dairy w/ rice hulls	450	19.201	0.801
479	Dairy w/ rice hulls	450	19.201	0.8
480	Dairy w/ rice hulls	500	19.202	0.8
481	Dairy w/ rice hulls	500	19.201	0.801

Table A2.1.2 (Continued)

482	Dairy w/ rice hulls	500	19.201	0.8
483	Dairy w/ rice hulls	500	19.202	0.802
484	Dairy w/ rice hulls	550	19.2	0.8
485	Dairy w/ rice hulls	550	19.202	0.802
486	Dairy w/ rice hulls	550	19.201	0.8
487	Dairy w/ rice hulls	550	19.201	0.801
488	Dairy w/ rice hulls	600	19.202	0.801
489	Dairy w/ rice hulls	600	19.2	0.802
490	Dairy w/ rice hulls	600	19.201	0.801
491	Dairy w/ rice hulls	600	19.202	0.801
492	Bull w/ sawdust	60	19.2	0.802
493	Bull w/ sawdust	60	19.2	0.8
494	Bull w/ sawdust	60	19.202	0.802
495	Bull w/ sawdust	60	19.201	0.801
496	Bull w/ sawdust	300	19.2	0.801
497	Bull w/ sawdust	300	19.202	0.8
498	Bull w/ sawdust	300	19.2	0.8
499	Bull w/ sawdust	300	19.202	0.801
500	Bull w/ sawdust	350	19.201	0.801
501	Bull w/ sawdust	350	19.201	0.8
502	Bull w/ sawdust	350	19.201	0.8
503	Bull w/ sawdust	350	19.201	0.802
504	Bull w/ sawdust	400	19.202	0.8
505	Bull w/ sawdust	400	19.201	0.801
506	Bull w/ sawdust	400	19.201	0.802
507	Bull w/ sawdust	400	19.202	0.802
508	Bull w/ sawdust	450	19.201	0.8
509	Bull w/ sawdust	450	19.2	0.8
510	Bull w/ sawdust	450	19.201	0.8
511	Bull w/ sawdust	450	19.202	0.802
512	Bull w/ sawdust	500	19.2	0.802
513	Bull w/ sawdust	500	19.202	0.801
514	Bull w/ sawdust	500	19.201	0.801
515	Bull w/ sawdust	500	19.202	0.8
516	Bull w/ sawdust	550	19.201	0.8
517	Bull w/ sawdust	550	19.202	0.8
518	Bull w/ sawdust	550	19.2	0.8
519	Bull w/ sawdust	550	19.201	0.801
520	Bull w/ sawdust	600	19.2	0.802
521	Bull w/ sawdust	600	19.202	0.802
522	Bull w/ sawdust	600	19.2	0.8
523	Bull w/ sawdust	600	19.2	0.8
524	Blank		19.2	0
525	Blank		19.201	0
526	Blank		19.201	0
527	Blank		19.201	0

Table A2.1.3 Jar component masses for 36 month incubation

Jar #	Feedstock	Temperature (°C)	Sand mass (g)	BC mass (g)
100	Bull w/ sawdust	60	19.2327	0.802
101	Bull w/ sawdust	60	19.2036	0.805
102	Bull w/ sawdust	60	19.2123	0.805
136	Bull w/ sawdust	300	19.2204	0.8096
137	Bull w/ sawdust	300	19.2038	0.8
138	Bull w/ sawdust	300	19.2102	0.8028
157	Bull w/ sawdust	350	19.2175	0.8074
158	Bull w/ sawdust	350	19.2166	0.8
159	Bull w/ sawdust	350	19.2311	0.8061
223	Bull w/ sawdust	400	19.2036	0.8068
224	Bull w/ sawdust	400	19.2735	0.801
225	Bull w/ sawdust	400	19.2329	0.8114
124	Bull w/ sawdust	450	19.2129	0.8068
125	Bull w/ sawdust	450	19.2022	0.804
126	Bull w/ sawdust	450	19.2056	0.8026
163	Bull w/ sawdust	500	19.2237	0.8028
164	Bull w/ sawdust	500	19.2173	0.8
165	Bull w/ sawdust	500	19.2188	0.8086
232	Bull w/ sawdust	550	19.231	0.8058
233	Bull w/ sawdust	550	19.236	0.802
234	Bull w/ sawdust	550	19.2031	0.8055
148	Bull w/ sawdust	600	19.2028	0.8064
149	Bull w/ sawdust	600	19.2264	0.802
150	Bull w/ sawdust	600	19.2088	0.8083
91	Corn Stalks	60	19.2024	0.8
92	Corn Stalks	60	19.2145	0.802
93	Corn Stalks	60	19.2123	0.807
217	Corn Stalks	300	19.2171	0.802
218	Corn Stalks	300	19.2287	0.8031
219	Corn Stalks	300	19.2313	0.8058
121	Corn Stalks	350	19.2438	0.806
122	Corn Stalks	350	19.2073	0.802
123	Corn Stalks	350	19.2048	0.8022
181	Corn Stalks	400	19.213	0.8002
182	Corn Stalks	400	19.2105	0.8
183	Corn Stalks	400	19.2174	0.8039
238	Corn Stalks	450	19.1957	0.8034
239	Corn Stalks	450	19.1904	0.802
240	Corn Stalks	450	19.2264	0.8032
178	Corn Stalks	500	19.2214	0.8027
179	Corn Stalks	500	19.2078	0.802
180	Corn Stalks	500	19.2232	0.8036

Table A2.1.3 (Continued)

229	Corn Stalks	550	19.2704	0.8042
230	Corn Stalks	550	19.2483	0.8
231	Corn Stalks	550	19.2424	0.8039
142	Corn Stalks	600	19.2369	0.8049
143	Corn Stalks	600	19.2244	0.8065
144	Corn Stalks	600	19.2117	0.8028
97	Dairy w/ rice hulls	60	19.2104	0.81
98	Dairy w/ rice hulls	60	19.2227	0.804
99	Dairy w/ rice hulls	60	19.2363	0.813
130	Dairy w/ Rice Hulls	300	19.2088	0.8033
131	Dairy w/ Rice Hulls	300	19.2146	0.806
132	Dairy w/ Rice Hulls	300	19.2133	0.8094
175	Dairy w/ Rice Hulls	350	19.2062	0.8043
176	Dairy w/ Rice Hulls	350	19.2043	0.801
177	Dairy w/ Rice Hulls	350	19.2068	0.8076
211	Dairy w/ Rice Hulls	400	19.218	0.8129
212	Dairy w/ Rice Hulls	400	19.2318	0.825
213	Dairy w/ Rice Hulls	400	19.2107	0.8049
196	Dairy w/ Rice Hulls	450	19.2195	0.811
197	Dairy w/ Rice Hulls	450	19.208	0.8
198	Dairy w/ Rice Hulls	450	19.2396	0.8152
139	Dairy w/ Rice Hulls	500	19.2116	0.8066
140	Dairy w/ Rice Hulls	500	19.21	0.801
141	Dairy w/ Rice Hulls	500	19.2074	0.8125
199	Dairy w/ Rice Hulls	550	19.21	0.8058
200	Dairy w/ Rice Hulls	550	19.2096	0.802
201	Dairy w/ Rice Hulls	550	19.2083	0.8059
235	Dairy w/ Rice Hulls	600	19.2433	0.8059
236	Dairy w/ Rice Hulls	600	19.2017	0.803
237	Dairy w/ Rice Hulls	600	19.1611	0.8081
82	Hazelnuts	60	19.2032	0.8
83	Hazelnuts	60	19.2464	0.8
84	Hazelnuts	60	19.2099	0.8
109	Hazelnuts	300	19.2032	0.8102
110	Hazelnuts	300	19.2041	0.81
111	Hazelnuts	300	19.214	0.8065
118	Hazelnuts	350	19.2088	0.8149
119	Hazelnuts	350	19.2177	0.809
120	Hazelnuts	350	19.208	0.8031
133	Hazelnuts	400	19.2197	0.8063
134	Hazelnuts	400	19.2199	0.82
135	Hazelnuts	400	19.205	0.8075
193	Hazelnuts	450	19.2283	0.8108
194	Hazelnuts	450	19.2245	0.817
195	Hazelnuts	450	19.2163	0.8076
166	Hazelnuts	500	19.2075	0.8025

Table A2.1.3 (Continued)

167	Hazelnuts	500	19.2222	0.806
168	Hazelnuts	500	19.2212	0.8059
226	Hazelnuts	550	19.2102	0.8074
227	Hazelnuts	550	19.2282	0.805
228	Hazelnuts	550	19.2452	0.8087
145	Hazelnuts	600	19.2119	0.8263
146	Hazelnuts	600	19.2254	0.814
147	Hazelnuts	600	19.2089	0.8047
94	Oak	60	19.2218	0.804
95	Oak	60	19.2066	0.816
96	Oak	60	19.2278	0.803
103	Oak	300	19.2087	0.803
104	Oak	300	19.2153	0.8
105	Oak	300	19.228	0.81
244	Oak	350	19.1869	0.8025
245	Oak	350	19.158	0.801
246	Oak	350	19.2469	0.8036
151	Oak	400	19.2214	0.8075
152	Oak	400	19.4015	0.8
153	Oak	400	19.2272	0.8102
190	Oak	450	19.2033	0.8133
191	Oak	450	19.2144	0.812
192	Oak	450	19.2413	0.8097
169	Oak	500	19.0421	0.8077
170	Oak	500	19.2183	0.812
171	Oak	500	19.2302	0.804
112	Oak	550	19.2134	0.8085
113	Oak	550	19.2238	0.8
114	Oak	550	19.2053	0.8035
160	Oak	600	19.236	0.8019
161	Oak	600	19.2099	0.801
162	Oak	600	19.2252	0.8024
85	Pine	60	19.2359	0.8137
86	Pine	60	19.1997	0.8
87	Pine	60	19.2142	0.8016
184	Pine	300	19.2209	0.8036
185	Pine	300	19.2085	0.8
186	Pine	300	19.1996	0.8119
172	Pine	350	19.2116	0.8075
173	Pine	350	19.2411	0.803
174	Pine	350	19.205	0.8034
247	Pine	400	19.2074	0.8059
248	Pine	400	19.2214	0.8
249	Pine	400	19.2095	0.804
208	Pine	450	19.2347	0.8038
209	Pine	450	19.2102	0.802
210	Pine	450	19.2104	0.8066

Table A2.1.3 (Continued)

205	Pine	500	19.2213	0.8041
206	Pine	500	19.2153	0.802
207	Pine	500	19.2329	0.8026
115	Pine	550	19.2066	0.8055
116	Pine	550	19.2192	0.8
117	Pine	550	19.2289	0.8143
187	Pine	600	19.2142	0.8124
188	Pine	600	19.2283	0.8
189	Pine	600	19.2084	0.8049
88	Poultry w/ sawdust	60	19.213	0.814
89	Poultry w/ sawdust	60	19.2153	0.808
90	Poultry w/ sawdust	60	19.2453	0.815
202	Poultry w/ sawdust	300	19.2151	0.803
203	Poultry w/ sawdust	300	19.213	0.8407
204	Poultry w/ sawdust	300	19.2126	0.8018
220	Poultry w/ sawdust	350	19.208	0.8215
221	Poultry w/ sawdust	350	19.2038	0.803
222	Poultry w/ sawdust	350	19.2116	0.8104
241	Poultry w/ sawdust	400	19.2031	0.8166
242	Poultry w/ sawdust	400	19.2045	0.804
243	Poultry w/ sawdust	400	19.2184	0.8184
106	Poultry w/ sawdust	450	19.2044	0.8035
107	Poultry w/ sawdust	450	19.2043	0.803
108	Poultry w/ sawdust	450	19.249	0.8417
214	Poultry w/ sawdust	500	19.2152	0.8
215	Poultry w/ sawdust	500	19.2164	0.8
216	Poultry w/ sawdust	500	19.2386	0.8071
127	Poultry w/ sawdust	550	19.2315	0.8091
128	Poultry w/ sawdust	550	19.2247	0.8
129	Poultry w/ sawdust	550	19.2076	0.8068
154	Poultry w/ sawdust	600	19.2361	0.8019
155	Poultry w/ sawdust	600	19.2332	0.8054
156	Poultry w/ sawdust	600	19.2445	0.808

Table A2.1.4 %C in sand-char samples after 5 months

Jar ID#	Feedstock	Temperature (°C)	5 month %C			
			Rep 1 (April)	Rep 2 (April)	Rep 3 (May)	Rep 4 (June)
492	Bull w/ sawdust	60	1.28		1.35	
493	Bull w/ sawdust	60	1.44		1.24	
494	Bull w/ sawdust	60	1.54			
495	Bull w/ sawdust	60	1.32			
496	Bull w/ sawdust	300	2.13		2.42	2.26
497	Bull w/ sawdust	300	2.96		2.38	2.38
498	Bull w/ sawdust	300			2.8	2.42
499	Bull w/ sawdust	300	1.87			
500	Bull w/ sawdust	350	2.26			
501	Bull w/ sawdust	350	2.64			
502	Bull w/ sawdust	350	2.50			
503	Bull w/ sawdust	350	2.32			
504	Bull w/ sawdust	400	3.02		2.222	
505	Bull w/ sawdust	400	2.61			
506	Bull w/ sawdust	400	2.61			
507	Bull w/ sawdust	400	3.24		2.749	
508	Bull w/ sawdust	450	1.99		3.054	
509	Bull w/ sawdust	450	3.11		2.887	
510	Bull w/ sawdust	450			2.845	
511	Bull w/ sawdust	450	2.82			
512	Bull w/ sawdust	500	3.10		2.911	
513	Bull w/ sawdust	500	3.06		2.981	
514	Bull w/ sawdust	500	3.25		3.291	
515	Bull w/ sawdust	500	2.56		2.557	
516	Bull w/ sawdust	550	2.44		2.938	
517	Bull w/ sawdust	550	3.95		3.229	
518	Bull w/ sawdust	550	3.22		2.987	
519	Bull w/ sawdust	550	3.23		3.270	
520	Bull w/ sawdust	600	3.09		3.500	
521	Bull w/ sawdust	600	3.74		3.148	
522	Bull w/ sawdust	600	2.93		3.456	3.50
523	Bull w/ sawdust	600	4.05		3.470	3.51
428	Corn stalks	60	1.32		1.04	
429	Corn stalks	60	1.09		1	
430	Corn stalks	60	1.16			
431	Corn stalks	60	1.21			
432	Corn stalks	300	2.34			2.32
433	Corn stalks	300	2.27			
434	Corn stalks	300	1.61		1.31	2.27
435	Corn stalks	300	2.44			2.41
436	Corn stalks	350	2.57			

Table A2.1.4 (Continued)

437	Corn stalks	350	2.58		
438	Corn stalks	350	2.60		
439	Corn stalks	350	2.39		
440	Corn stalks	400	2.87		
441	Corn stalks	400	2.48		
442	Corn stalks	400	2.47		
443	Corn stalks	400	2.62		
444	Corn stalks	450	3.04		
445	Corn stalks	450	2.70		
446	Corn stalks	450	2.64		
447	Corn stalks	450	2.50		
448	Corn stalks	500	2.88		
449	Corn stalks	500	2.87		
450	Corn stalks	500	2.70		
451	Corn stalks	500	2.61		
452	Corn stalks	550	3.12		
453	Corn stalks	550	3.00		
454	Corn stalks	550	3.01		
455	Corn stalks	550	2.81		
456	Corn stalks	600	2.68		
457	Corn stalks	600	2.79		
458	Corn stalks	600	3.00		
459	Corn stalks	600	2.51		
460	Dairy w/ rice hulls	60	1.28	1.37	
461	Dairy w/ rice hulls	60	1.27	1.17	
462	Dairy w/ rice hulls	60	1.36		
463	Dairy w/ rice hulls	60	1.38		
464	Dairy w/ rice hulls	300	2.78	1.59	
465	Dairy w/ rice hulls	300	2.73	1.53	
466	Dairy w/ rice hulls	300	2.35		2.35
467	Dairy w/ rice hulls	300	2.87		2.59
468	Dairy w/ rice hulls	350	2.52		
469	Dairy w/ rice hulls	350	2.45		
470	Dairy w/ rice hulls	350	2.40		
471	Dairy w/ rice hulls	350	2.44		
472	Dairy w/ rice hulls	400	2.33	2.71	
473	Dairy w/ rice hulls	400	3.06	2.25	
474	Dairy w/ rice hulls	400	2.57		
475	Dairy w/ rice hulls	400	2.94		
476	Dairy w/ rice hulls	450	2.59		
477	Dairy w/ rice hulls	450	2.83		
478	Dairy w/ rice hulls	450	3.00		
479	Dairy w/ rice hulls	450	3.05		
480	Dairy w/ rice hulls	500	3.04		3.04
481	Dairy w/ rice hulls	500	2.91		
482	Dairy w/ rice hulls	500	3.03		

Table A2.1.4 (Continued)

483	Dairy w/ rice hulls	500	3.22			3.08
484	Dairy w/ rice hulls	550	2.90			
485	Dairy w/ rice hulls	550	2.92			
486	Dairy w/ rice hulls	550	3.07			
487	Dairy w/ rice hulls	550	3.07			
488	Dairy w/ rice hulls	600	2.93			
489	Dairy w/ rice hulls	600	2.99			
490	Dairy w/ rice hulls	600	3.09			
491	Dairy w/ rice hulls	600	3.44		1.86	
300	Hazelnuts	60	1.75	2.69		
301	Hazelnuts	60	1.96	2.04		
302	Hazelnuts	60	1.97	2.06		
303	Hazelnuts	60	1.92	2.02		
304	Hazelnuts	300	2.02	2.83		
305	Hazelnuts	300	0.03	2.68		
306	Hazelnuts	300	1.66	2.85		
307	Hazelnuts	300	3.56	2.66		
308	Hazelnuts	350	1.67	2.62		
309	Hazelnuts	350	2.34	2.92		
310	Hazelnuts	350	4.32	2.66		
311	Hazelnuts	350	2.21	2.63		
312	Hazelnuts	400	1.05	2.73		
313	Hazelnuts	400	3.00	3.64		
314	Hazelnuts	400	2.12	2.92		
315	Hazelnuts	400	3.53	3.45		
316	Hazelnuts	450	0.79	3.16		
317	Hazelnuts	450	2.07	3.23		
318	Hazelnuts	450	0.79	2.36		
319	Hazelnuts	450	1.63	2.52		
320	Hazelnuts	500	2.47	3.38		
321	Hazelnuts	500	1.99	3.04		
322	Hazelnuts	500	1.95	3.80		
323	Hazelnuts	500	4.00	2.79		
324	Hazelnuts	550	2.26	3.86		
325	Hazelnuts	550	2.00	2.74		
326	Hazelnuts	550	2.54	2.79		
327	Hazelnuts	550	1.96	3.87		
328	Hazelnuts	600	2.42	3.40		
329	Hazelnuts	600	2.13	2.63		
330	Hazelnuts	600	2.24	3.13		
331	Hazelnuts	600	1.88	3.55		
364	Oak	60	1.71		2	
365	Oak	60	1.86		1.63	
366	Oak	60			1.63	
367	Oak	60	2.03			
368	Oak	300	2.59			
369	Oak	300	2.29			

Table A2.1.4 (Continued)

370	Oak	300	2.11			
371	Oak	300	2.24			
372	Oak	350	3.05			3.22
373	Oak	350				2.82
374	Oak	350	3.08			
375	Oak	350	2.56			
376	Oak	400				2.87
377	Oak	400	2.93			
378	Oak	400				2.87
379	Oak	400	3.10			3.34
380	Oak	450	3.33			3.39
381	Oak	450				3.26
382	Oak	450				3.41
383	Oak	450				3.16
384	Oak	500	3.21			
385	Oak	500	3.34			
386	Oak	500	3.06			
387	Oak	500	3.35			
388	Oak	550	3.09			3.17
389	Oak	550	3.29			3.52
390	Oak	550	2.16			2.31
391	Oak	550	3.39			3.53
392	Oak	600	3.46			3.56
393	Oak	600	3.27			3.18
394	Oak	600	3.39			3.80
395	Oak	600	2.12			2.42
332	Pine	60	1.99		1.2	
333	Pine	60	1.60	1.57		
334	Pine	60	1.78	1.82		
335	Pine	60	1.73	1.81		
336	Pine	300	2.39	2.54		2.53
337	Pine	300	3.21	2.61		
338	Pine	300	2.37	2.58		2.43
339	Pine	300	2.80	2.72		2.68
340	Pine	350	2.80	2.29		
341	Pine	350	2.79	2.63		2.90
342	Pine	350	2.85	3.01		3.01
343	Pine	350	2.92	2.61		
344	Pine	400	3.06	2.77		
345	Pine	400	3.09	3.36		
346	Pine	400	3.23	2.28		
347	Pine	400	2.94	3.96		
348	Pine	450	3.39	1.85		3.45
349	Pine	450	3.16	3.32		3.13
350	Pine	450	2.42	2.65		2.90
351	Pine	450	2.60	3.87		2.71
352	Pine	500	3.29			3.19

Table A2.1.4 (Continued)

353	Pine	500	3.30			3.32
354	Pine	500	3.25			3.23
355	Pine	500	3.70			3.58
356	Pine	550	3.50		1.15	3.21
357	Pine	550	2.55	2.37	0.88	2.70
358	Pine	550	3.65	3.78		3.31
359	Pine	550	3.19	3.08		
360	Pine	600	3.54	3.57		3.69
361	Pine	600	2.24	2.97	0.85	3.74
362	Pine	600	3.58	3.27		3.56
363	Pine	600	3.77	3.40		3.93
396	Poultry w/ sawdust	60	0.45		0.504	
397	Poultry w/ sawdust	60	0.51		0.527	
398	Poultry w/ sawdust	60	0.47			
399	Poultry w/ sawdust	60	0.50			
400	Poultry w/ sawdust	300	1.10			1.03
401	Poultry w/ sawdust	300	1.06			1.09
402	Poultry w/ sawdust	300	1.06			1.11
403	Poultry w/ sawdust	300	1.14			1.18
404	Poultry w/ sawdust	350	0.74			
405	Poultry w/ sawdust	350	0.87			
406	Poultry w/ sawdust	350	1.01		0.89	
407	Poultry w/ sawdust	350	0.95			1.02
408	Poultry w/ sawdust	400	0.72			
409	Poultry w/ sawdust	400	0.67			
410	Poultry w/ sawdust	400	0.73			
411	Poultry w/ sawdust	400	0.69			
412	Poultry w/ sawdust	450	0.64			
413	Poultry w/ sawdust	450	0.63			
414	Poultry w/ sawdust	450	0.66			
415	Poultry w/ sawdust	450	0.66			
416	Poultry w/ sawdust	500	0.61			
417	Poultry w/ sawdust	500	0.64			
418	Poultry w/ sawdust	500	0.71			
419	Poultry w/ sawdust	500	0.67			
420	Poultry w/ sawdust	550	0.66			
421	Poultry w/ sawdust	550	0.71			
422	Poultry w/ sawdust	550	0.91		0.85	
423	Poultry w/ sawdust	550	0.67			
424	Poultry w/ sawdust	600	0.60			
425	Poultry w/ sawdust	600	0.70			
426	Poultry w/ sawdust	600	0.69			
427	Poultry w/ sawdust	600	0.64			

Table A2.1.5 %C in sand-char samples after 36 months

Jar ID#	Feedstock	Temperature (°C)	36 month %C Rep 1 (April)	Rep 2 (May)	Rep 4 (June)
100	Bull w/ sawdust	60	0.90		
101	Bull w/ sawdust	60	0.92		
102	Bull w/ sawdust	60	1.00		
136	Bull w/ sawdust	300	3.11	1.976	
137	Bull w/ sawdust	300	1.85	2.632	
138	Bull w/ sawdust	300	2.53	2.023	
157	Bull w/ sawdust	350	0.65	2.843	
158	Bull w/ sawdust	350	2.63		
159	Bull w/ sawdust	350		2.285	
223	Bull w/ sawdust	400	2.70		
224	Bull w/ sawdust	400	2.92		
225	Bull w/ sawdust	400	2.71		
124	Bull w/ sawdust	450	2.50		
125	Bull w/ sawdust	450	2.00	2.986	
126	Bull w/ sawdust	450	3.74	2.628	
163	Bull w/ sawdust	500	2.78		
164	Bull w/ sawdust	500	2.74		
165	Bull w/ sawdust	500	2.41		
232	Bull w/ sawdust	550	2.43	2.459	
233	Bull w/ sawdust	550	2.87		
234	Bull w/ sawdust	550	3.01	2.865	
148	Bull w/ sawdust	600	4.88	3.355	3.452
149	Bull w/ sawdust	600	3.30	3.061	
150	Bull w/ sawdust	600	2.73	3.298	
91	Corn Stalks	60	0.33		
92	Corn Stalks	60	0.29		
93	Corn Stalks	60	0.31		
217	Corn Stalks	300	2.17	1.980	
218	Corn Stalks	300	1.90		
219	Corn Stalks	300	1.72		
121	Corn Stalks	350	1.95	2.488	
122	Corn Stalks	350	2.60	1.860	
123	Corn Stalks	350	2.13		
181	Corn Stalks	400	2.10	2.100	
182	Corn Stalks	400	2.30		
183	Corn Stalks	400	2.51	2.586	
238	Corn Stalks	450	2.46		
239	Corn Stalks	450	2.85		
240	Corn Stalks	450	2.61		
178	Corn Stalks	500	2.42		

Table A2.1.5 (Continued)

179	Corn Stalks	500	2.29		
180	Corn Stalks	500	2.44		
229	Corn Stalks	550	2.70		2.78
230	Corn Stalks	550	2.05	1.924	
231	Corn Stalks	550	2.98		3.07
142	Corn Stalks	600	1.66	2.502	
143	Corn Stalks	600	2.55		2.60
144	Corn Stalks	600	3.10		3.32
97	Dairy w/ Rice Hulls	60	0.77		
98	Dairy w/ Rice Hulls	60	0.70		
99	Dairy w/ Rice Hulls	60	0.84		
130	Dairy w/ Rice Hulls	300	1.75		
131	Dairy w/ Rice Hulls	300	1.95		
132	Dairy w/ Rice Hulls	300		2.131	
175	Dairy w/ Rice Hulls	350	2.40		
176	Dairy w/ Rice Hulls	350	2.22		
177	Dairy w/ Rice Hulls	350	2.52		
211	Dairy w/ Rice Hulls	400	2.70		
212	Dairy w/ Rice Hulls	400	2.70		
213	Dairy w/ Rice Hulls	400	2.90		
196	Dairy w/ Rice Hulls	450	2.86		
197	Dairy w/ Rice Hulls	450	2.32	2.264	
198	Dairy w/ Rice Hulls	450	2.93		
139	Dairy w/ Rice Hulls	500		2.861	
140	Dairy w/ Rice Hulls	500		2.578	
141	Dairy w/ Rice Hulls	500		2.380	
199	Dairy w/ Rice Hulls	550	2.37		
200	Dairy w/ Rice Hulls	550		2.839	
201	Dairy w/ Rice Hulls	550		2.936	
235	Dairy w/ Rice Hulls	600	3.50	3.230	
236	Dairy w/ Rice Hulls	600	3.11	3.026	
237	Dairy w/ Rice Hulls	600	2.87	2.837	
82	Hazelnuts	60	2.18		
83	Hazelnuts	60	1.74		
84	Hazelnuts	60	1.61		
109	Hazelnuts	300	2.85		
110	Hazelnuts	300	2.61		
111	Hazelnuts	300	2.80		
118	Hazelnuts	350	2.88		
119	Hazelnuts	350	2.05		
120	Hazelnuts	350	2.49		
133	Hazelnuts	400	2.26		
134	Hazelnuts	400	3.29		
135	Hazelnuts	400	2.47		
193	Hazelnuts	450	2.60		

Table A2.1.5 (Continued)

194	Hazelnuts	450	3.09			
195	Hazelnuts	450	2.68			
166	Hazelnuts	500	3.65			
167	Hazelnuts	500	3.12			
168	Hazelnuts	500	3.12			
226	Hazelnuts	550	2.84			
227	Hazelnuts	550	2.81			
228	Hazelnuts	550	3.50			
145	Hazelnuts	600	1.56			
146	Hazelnuts	600	2.36			
147	Hazelnuts	600	3.31			
94	Oak	60	1.60	1.650		
95	Oak	60	1.18	1.270		
96	Oak	60	1.38		1.384	
103	Oak	300	2.46	2.473		
104	Oak	300	1.93	1.991		
105	Oak	300	2.38			
244	Oak	350	2.21	2.127	2.203	
245	Oak	350	3.25	3.301	3.305	
246	Oak	350	2.91			2.89
151	Oak	400	3.36			3.55
152	Oak	400	3.37			2.75
153	Oak	400	1.53	2.924		
190	Oak	450	3.24			
191	Oak	450	3.01			
192	Oak	450	3.51			
169	Oak	500	3.45	3.442		
170	Oak	500	2.69	2.722		
171	Oak	500	3.04			
112	Oak	550	3.21			3.72
113	Oak	550	4.68	4.281	4.288	
114	Oak	550	3.14			2.79
160	Oak	600	3.30			
161	Oak	600	3.79			
162	Oak	600	3.26			
85	Pine	60	1.40			
86	Pine	60	1.63			
87	Pine	60	1.53			
184	Pine	300	2.25			
185	Pine	300	2.24			
186	Pine	300	2.00			
172	Pine	350	2.75			
173	Pine	350	2.58			
174	Pine	350	2.89			
247	Pine	400	2.95			2.92
248	Pine	400	2.27	2.174	2.261	

Table A2.1.5 (Continued)

249	Pine	400	3.25	3.166	3.241	
208	Pine	450	2.94			
209	Pine	450	2.82			
210	Pine	450	3.01			
205	Pine	500	2.68			
206	Pine	500	2.98			
207	Pine	500	3.02			
115	Pine	550	3.44	3.473		
116	Pine	550	2.67	3.354		
117	Pine	550	2.69			
187	Pine	600	3.08			
188	Pine	600	3.10			
189	Pine	600	3.07			
88	Poultry w/ sawdust	60	0.36	0.378		
89	Poultry w/ sawdust	60	0.59	0.646		
90	Poultry w/ sawdust	60	0.27	0.312		
202	Poultry w/ sawdust	300	0.84	1.27	0.86	
203	Poultry w/ sawdust	300	0.77		0.81	
204	Poultry w/ sawdust	300	0.69	0.65		
220	Poultry w/ sawdust	350	0.84			0.88
221	Poultry w/ sawdust	350	1.01	0.97		
222	Poultry w/ sawdust	350	0.78	0.75		
241	Poultry w/ sawdust	400	0.76			
242	Poultry w/ sawdust	400	0.73			
243	Poultry w/ sawdust	400	0.74			
106	Poultry w/ sawdust	450	0.31			0.67
107	Poultry w/ sawdust	450	0.57	0.73	0.78	
108	Poultry w/ sawdust	450	0.34			0.61
214	Poultry w/ sawdust	500	0.71			
215	Poultry w/ sawdust	500	0.72			
216	Poultry w/ sawdust	500	0.84			
127	Poultry w/ sawdust	550	0.53	0.77		
128	Poultry w/ sawdust	550	0.33			0.81
129	Poultry w/ sawdust	550	0.38			0.61
154	Poultry w/ sawdust	600		0.58	0.63	
155	Poultry w/ sawdust	600		0.64	0.69	
156	Poultry w/ sawdust	600		0.62	0.67	

Table A2.1.6 / 1.S4. Total elemental analysis ICP results (mg element / kg BC)

Feedstock	Temp (°C)	Al3961		As1890	
		Mean	SD	Mean	SD
Bull	60	111.4	11.2	-3.2	2.0
	300	349.4	115.1	0.3	0.8
	350	298.5	29.7	-1.4	1.1
	400	312.1	51.6	-0.7	0.6
	450	273.0	25.4	-0.2	1.8
	500	368.6	49.1	-0.5	0.8
	550	406.8	66.1	-0.1	1.2
	600	312.4	11.9	-0.7	1.4
Corn	60	398.9	79.4	-3.5	5.6
	300	1156.1	66.0	-0.6	0.4
	350	703.4	30.4	-1.2	3.3
	400	917.7	87.2	0.9	1.5
	450	861.2	97.2	-0.9	0.5
	500	1303.8	90.8	0.9	0.8
	550	1083.9	97.5	0.3	0.7
	600	1463.7	255.2	0.2	0.7
Dairy	60	63.1	4.6	-4.9	2.1
	300	145.1	18.2	-0.4	0.5
	350	144.9	24.1	0.5	1.1
	400	146.1	36.8	0.6	1.8
	450	187.4	76.8	-0.5	2.4
	500	162.0	163.2	-3.4	12.2
	550	210.1	40.6	0.0	0.8
	600	160.9	18.6	-0.3	0.2
Oak	60	22.1	1.2	-2.8	1.1
	300	4.6	2.0	1.2	0.7
	350	71.6	30.7	0.4	0.8
	400	11.7	10.5	0.0	1.6
	450	33.2	11.0	0.0	0.6
	500	17.8	17.2	-0.5	0.6
	550	54.4	52.7	-0.7	1.6
	600	168.6	81.9	0.1	1.2
Pine	60	78.7	1.6	-4.5	1.2
	300	722.5	159.9	0.2	1.0
	350	86.4	5.4	0.3	1.4
	400	154.9	69.3	0.1	0.3
	450	46.6	42.0	0.3	0.6
	500	59.7	5.7	0.7	1.5
	550	30.2	6.9	2.3	0.7
	600	182.3	37.5	-0.8	0.4
Poultry	60	949.1	122.2	-47.4	24.1
	300	1015.9	70.8	5.0	9.8
	350	973.2	36.3	1.0	7.2
	400	828.9	38.5	1.7	9.1
	450	821.6	60.9	1.2	3.0
	500	1318.8	155.0	6.7	6.2
	550	978.9	125.9	3.9	5.6
	600	1095.3	48.8	-5.0	4.7

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**B_2496**		**Ba4934**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	6.3	4.2	30.7	1.8
	300	20.8	4.5	58.4	1.7
	350	27.8	3.3	58.9	0.4
	400	19.8	2.9	75.5	1.6
	450	25.2	6.2	66.9	0.6
	500	39.3	5.2	76.9	2.5
	550	30.0	6.2	79.5	2.9
	600	31.0	8.5	76.5	1.4
Corn	60	-13.6	6.6	22.6	1.5
	300	20.3	9.1	50.7	0.5
	350	16.0	7.8	55.9	1.4
	400	6.0	1.0	56.3	1.3
	450	19.7	11.2	71.6	4.4
	500	9.4	1.1	72.0	1.1
	550	14.2	2.8	83.1	1.4
	600	10.6	4.2	92.2	9.2
Dairy	60	-2.0	1.9	4.4	0.4
	300	22.9	2.0	7.1	0.1
	350	27.5	2.5	6.7	0.4
	400	26.5	2.8	7.0	0.2
	450	23.2	2.6	7.7	0.4
	500	-47.2	11.5	-12.1	0.4
	550	35.3	6.4	9.5	0.9
	600	30.2	3.0	7.8	0.1
Oak	60	-18.5	11.2	12.7	0.8
	300	2.5	1.2	17.8	0.0
	350	1.7	4.3	30.1	1.7
	400	7.3	4.4	26.8	0.6
	450	-0.3	1.9	36.7	1.0
	500	6.4	8.2	34.8	0.9
	550	-4.5	2.0	27.2	0.4
	600	-6.9	2.5	34.3	3.3
Pine	60	-16.1	8.4	21.8	0.7
	300	3.2	1.1	5.0	0.1
	350	0.6	2.7	5.1	0.3
	400	3.7	1.7	10.0	0.7
	450	-1.2	3.3	16.8	10.8
	500	-3.9	2.6	9.6	0.4
	550	-1.3	2.5	12.6	1.4
	600	-2.2	5.7	13.5	5.6
Poultry	60	-76.8	36.8	23.4	1.6
	300	-0.2	21.3	7.5	0.3
	350	8.9	26.4	9.9	2.7
	400	-54.4	11.6	1.3	0.5
	450	-13.6	13.1	6.8	2.3
	500	-8.3	8.1	18.0	7.4
	550	22.5	13.8	32.3	42.0
	600	-16.3	25.3	10.2	3.0

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Ca3179**		**Cd2265**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	3883.0	255.9	-0.3	0.3
	300	9411.6	534.5	0.3	0.1
	350	10518.4	1042.1	0.2	0.1
	400	10087.8	132.0	0.2	0.0
	450	8449.8	322.6	0.2	0.2
	500	9431.9	469.1	0.2	0.0
	550	11109.0	409.3	0.0	0.1
	600	9385.8	400.5	0.1	0.1
Corn	60	4929.3	1250.2	-0.4	0.3
	300	6479.6	9.9	0.0	0.2
	350	6136.4	170.1	0.0	0.2
	400	7253.5	101.3	0.1	0.2
	450	7316.6	229.2	0.2	0.1
	500	11698.8	1395.8	-0.1	0.2
	550	9803.8	317.8	0.1	0.1
	600	9382.7	246.3	0.0	0.1
Dairy	60	5437.3	409.3	-0.3	0.2
	300	11094.4	1578.8	0.2	0.1
	350	10859.3	1035.6	0.0	0.1
	400	12807.5	2070.6	0.1	0.1
	450	13472.9	998.7	-0.1	0.2
	500	12568.8	1885.7	-0.6	0.6
	550	25701.6	3053.1	0.1	0.1
	600	13996.8	1456.8	0.1	0.1
Oak	60	587.3	15.3	-0.3	0.2
	300	751.7	9.5	-0.1	0.2
	350	1096.6	61.3	0.3	0.2
	400	1060.5	57.7	0.2	0.1
	450	1023.5	14.9	0.1	0.1
	500	1538.1	13.6	0.1	0.1
	550	1608.8	93.7	0.1	0.1
	600	1210.0	13.0	0.1	0.1
Pine	60	1479.5	157.2	0.7	1.2
	300	2927.0	281.7	0.4	0.0
	350	1939.7	39.2	0.7	0.3
	400	2246.7	690.1	0.3	0.3
	450	2194.2	115.1	1.0	0.1
	500	2741.5	59.4	0.0	0.1
	550	2255.4	11.9	0.1	0.1
	600	2167.3	75.9	0.0	0.2
Poultry	60	153209.1	4914.6	-2.0	1.6
	300	157530.6	20009.1	2.4	1.2
	350	215647.8	7979.6	2.3	0.3
	400	265728.9	13090.4	1.1	0.7
	450	267804.0	8897.6	1.7	0.7
	500	204205.1	8964.0	2.6	0.4
	550	252608.1	27560.1	2.0	0.2
	600	242788.1	21806.7	2.8	1.0

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Cd2288**		**Co2286**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	-0.7	0.4	1.0	0.5
	300	0.3	0.3	1.1	0.2
	350	0.2	0.2	1.2	0.1
	400	0.3	0.1	1.2	0.1
	450	0.3	0.1	1.0	0.1
	500	0.0	0.0	1.2	0.0
	550	0.1	0.1	1.4	0.2
	600	0.0	0.0	1.0	0.2
Corn	60	-0.9	0.6	0.7	0.6
	300	-0.2	0.2	0.8	0.1
	350	0.0	0.3	0.6	0.6
	400	0.0	0.1	0.4	0.2
	450	0.0	0.1	0.6	0.1
	500	0.0	0.1	0.7	0.0
	550	0.2	0.1	0.7	0.2
	600	0.0	0.1	0.6	0.2
Dairy	60	-0.5	0.4	0.9	0.3
	300	0.0	0.1	1.2	0.2
	350	0.2	0.1	1.2	0.1
	400	-0.1	0.1	2.0	1.3
	450	-0.1	0.2	1.6	0.6
	500	0.1	0.4	0.2	1.2
	550	0.1	0.1	1.7	0.2
	600	0.1	0.1	1.5	0.1
Oak	60	-0.6	0.2	0.3	0.2
	300	0.0	0.1	0.2	0.1
	350	0.3	0.2	0.6	0.4
	400	0.0	0.1	0.1	0.2
	450	0.0	0.1	0.1	0.1
	500	0.0	0.1	0.0	0.2
	550	0.0	0.1	0.1	0.3
	600	0.0	0.1	0.2	0.1
Pine	60	0.7	0.8	0.0	0.1
	300	0.4	0.1	0.3	0.3
	350	0.6	0.3	-0.1	0.5
	400	0.2	0.0	0.2	0.2
	450	0.6	0.1	0.2	0.1
	500	0.0	0.2	0.1	0.1
	550	0.1	0.1	0.1	0.2
	600	0.0	0.1	0.1	0.3
Poultry	60	-5.7	2.0	2.6	1.2
	300	1.6	0.4	1.8	0.5
	350	2.0	0.5	0.1	0.3
	400	1.5	0.9	1.2	0.9
	450	1.2	0.5	1.0	1.1
	500	2.2	1.4	2.1	1.4
	550	0.2	0.9	-0.7	1.1
	600	2.4	2.7	0.7	0.9

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Cr2677**		**Cu3247**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	1.7	0.6	13.9	0.4
	300	1.6	0.3	52.7	12.1
	350	2.0	1.1	35.6	1.0
	400	1.2	0.3	42.0	1.3
	450	1.0	0.4	31.0	0.7
	500	1.3	0.2	42.5	3.0
	550	18.6	26.7	44.2	4.3
	600	0.9	0.0	50.2	1.9
Corn	60	1.7	0.9	6.4	1.3
	300	14.4	4.2	44.8	5.2
	350	2.2	0.9	21.5	1.7
	400	3.1	1.8	15.7	0.2
	450	2.6	0.8	16.2	1.3
	500	2.7	0.3	26.3	0.1
	550	2.5	0.2	25.9	15.7
	600	3.5	0.9	32.7	1.0
Dairy	60	1.4	0.5	164.4	12.6
	300	1.5	0.2	252.0	22.5
	350	3.7	2.5	326.0	5.9
	400	1.7	1.6	300.8	13.9
	450	1.5	1.0	402.5	49.5
	500	0.9	1.5	346.7	38.0
	550	1.4	0.1	498.6	26.6
	600	1.2	0.1	429.4	11.9
Oak	60	0.6	0.8	106.4	12.0
	300	0.0	0.1	17.1	4.2
	350	14.5	17.0	120.1	16.7
	400	0.2	0.0	24.6	7.1
	450	0.7	0.1	48.7	13.2
	500	1.1	1.2	33.7	3.2
	550	0.9	0.1	25.8	1.0
	600	0.9	0.3	327.4	160.3
Pine	60	1.7	0.8	131.2	25.3
	300	1.2	0.1	5.7	0.1
	350	0.7	0.4	12.6	3.4
	400	21.5	30.3	21.1	2.1
	450	1.0	1.0	6073.7	484.1
	500	1.4	0.4	95.1	22.8
	550	4.3	0.9	65.3	3.9
	600	2.9	1.8	35.8	1.4
Poultry	60	18.2	3.7	53.9	6.9
	300	16.6	2.1	87.7	9.9
	350	14.1	2.0	64.9	3.1
	400	12.0	1.4	58.9	5.8
	450	9.8	0.6	54.4	5.7
	500	19.2	1.0	108.0	3.1
	550	11.5	2.0	63.6	17.5
	600	14.8	1.9	85.9	22.1

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Fe2599**		**Fe2714**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	67.2	7.1	75.9	2.1
	300	376.1	158.4	373.6	158.7
	350	322.4	104.1	319.0	103.6
	400	255.6	32.0	255.1	29.9
	450	175.8	39.9	173.1	38.2
	500	266.8	26.3	263.6	25.3
	550	417.4	218.6	413.0	213.7
	600	310.9	116.6	306.4	116.6
Corn	60	256.6	58.7	272.4	70.1
	300	963.1	13.9	953.7	12.1
	350	558.4	44.7	559.7	47.5
	400	897.1	124.2	884.2	123.6
	450	815.2	22.7	802.6	24.0
	500	1063.2	139.4	1051.4	139.2
	550	845.3	151.0	836.5	148.8
	600	1361.9	289.8	1337.5	276.2
Dairy	60	99.3	24.0	105.0	27.6
	300	208.4	21.8	205.4	23.8
	350	316.7	55.2	311.7	53.5
	400	304.7	138.4	314.8	131.7
	450	349.4	52.3	351.3	60.4
	500	396.2	89.0	393.7	91.9
	550	754.2	229.5	744.3	223.1
	600	398.1	26.5	392.5	25.7
Oak	60	40.2	14.4	42.3	16.2
	300	5.2	1.6	3.7	1.9
	350	2673.9	2143.6	2562.8	1992.0
	400	169.1	106.9	171.2	108.7
	450	162.1	138.8	164.4	141.5
	500	16.4	13.5	13.8	13.6
	550	323.3	297.0	324.5	294.1
	600	158.3	84.9	159.6	85.6
Pine	60	126.3	6.7	135.9	7.3
	300	148.7	26.4	148.9	29.1
	350	40.4	8.8	35.5	17.4
	400	1165.7	582.5	1137.9	552.2
	450	418.1	314.2	417.8	309.2
	500	68.6	40.2	69.6	39.6
	550	109.6	135.3	110.1	134.3
	600	820.0	971.9	797.7	933.0
Poultry	60	971.6	150.4	1037.0	146.1
	300	1778.9	572.1	1774.7	584.7
	350	1463.7	180.2	1450.2	195.4
	400	1276.0	133.2	1246.6	134.5
	450	1069.2	58.7	1051.8	64.3
	500	2034.1	197.9	2045.2	191.2
	550	1513.4	264.0	1484.3	243.3
	600	1521.8	80.5	1512.1	85.9

Table A2.1.6 / 1.S4. (Continued)

Feedstock	Temp (°C)	K_4047		K_7664	
		Mean	**SD**	**Mean**	**SD**
Bull	60	5716.9	1730.8	9533.4	281.8
	300	18421.9	1189.0	20016.9	500.8
	350	22621.2	762.6	24389.1	233.0
	400	27736.5	552.4	28938.9	380.5
	450	29797.2	1168.6	30404.7	195.2
	500	32449.6	1243.7	33476.8	461.8
	550	31621.6	1105.1	32808.1	229.4
	600	35453.3	262.7	35819.9	197.4
Corn	60	3420.9	1378.2	7986.8	151.3
	300	17259.6	1732.0	17052.4	149.4
	350	18146.8	2225.9	21486.4	156.7
	400	20971.4	722.7	20233.7	319.8
	450	23708.5	478.4	25706.9	14.1
	500	25848.7	566.8	24817.0	670.6
	550	22891.5	560.1	23928.9	273.4
	600	25932.0	361.4	24615.8	203.6
Dairy	60	1486.4	210.5	3860.8	194.2
	300	7763.3	590.6	8985.8	266.7
	350	8900.9	338.1	10073.8	89.7
	400	8718.3	511.1	10344.7	94.9
	450	9299.0	2734.2	11755.8	113.5
	500	11878.1	2798.8	9630.4	280.5
	550	12031.2	226.2	13387.8	122.4
	600	11643.0	500.6	13236.0	234.6
Oak	60	-1844.1	288.7	251.3	24.9
	300	874.5	333.7	724.7	57.2
	350	956.9	81.1	1147.1	51.5
	400	1932.4	272.2	1462.1	35.3
	450	1485.3	260.6	1663.7	23.8
	500	830.9	468.1	1171.5	73.7
	550	1301.9	591.1	1274.0	71.2
	600	2037.7	357.4	2061.3	40.1
Pine	60	-1686.4	381.6	195.7	36.1
	300	636.1	206.1	692.5	90.7
	350	1373.8	3526.6	386.5	26.6
	400	141.1	392.3	372.8	25.3
	450	566.3	450.5	996.4	54.0
	500	741.6	49.8	681.8	40.6
	550	748.5	308.7	733.5	30.9
	600	1016.5	359.4	775.1	74.4
Poultry	60	464.6	9685.0	24052.7	715.1
	300	40649.7	1792.8	40012.6	3566.2
	350	30464.1	2829.7	31751.4	1253.0
	400	33702.0	3169.9	28109.3	2656.4
	450	26712.8	3755.7	27399.9	1819.7
	500	54851.8	875.4	48615.9	1228.7
	550	32296.7	8468.9	32126.1	7833.3
	600	44890.2	6491.6	36774.6	6007.5

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Mg2790**		**Mn2576**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	1835.5	84.7	23.3	6.2
	300	3952.1	134.7	137.0	19.8
	350	4276.9	228.0	150.5	5.2
	400	4841.3	6.5	141.1	13.8
	450	4313.8	49.8	121.3	9.5
	500	4925.2	142.3	145.8	15.9
	550	5217.7	239.5	177.8	68.6
	600	5071.4	147.1	164.9	26.1
Corn	60	3565.5	750.7	56.1	7.8
	300	5882.8	31.2	141.6	8.9
	350	6306.7	22.4	128.6	5.1
	400	6582.9	126.4	160.4	4.6
	450	8030.6	117.5	175.5	14.3
	500	9509.6	653.7	198.8	9.0
	550	8890.8	101.1	207.8	30.5
	600	8582.3	123.3	225.5	16.4
Dairy	60	1801.0	68.0	15.0	4.6
	300	3933.8	120.6	51.7	11.7
	350	4278.1	88.6	55.9	7.4
	400	4258.2	186.6	52.7	17.0
	450	5067.9	313.5	77.8	11.0
	500	4609.8	405.1	78.7	5.6
	550	6356.6	373.9	112.5	3.8
	600	5366.3	121.0	98.3	2.3
Oak	60	62.7	2.7	7.2	0.5
	300	45.7	1.5	11.6	0.5
	350	41.2	5.5	23.2	10.7
	400	61.1	2.9	15.5	1.7
	450	25.2	0.2	23.9	14.8
	500	57.1	1.1	21.8	1.0
	550	41.5	4.2	27.4	5.2
	600	100.1	1.1	22.9	1.4
Pine	60	142.6	6.8	27.7	2.0
	300	680.5	29.1	141.5	5.4
	350	388.5	4.7	131.0	4.7
	400	481.9	12.1	257.9	20.6
	450	666.6	16.0	296.6	74.7
	500	795.6	5.2	259.0	41.0
	550	707.3	4.8	298.0	22.7
	600	603.5	15.8	349.3	25.5
Poultry	60	6062.6	293.3	282.3	23.0
	300	8914.4	368.4	449.7	23.5
	350	7308.9	74.8	425.9	22.6
	400	7163.6	583.5	397.1	35.4
	450	6388.0	191.8	364.0	17.1
	500	10436.2	274.8	565.9	21.2
	550	7276.9	1223.0	431.4	79.8
	600	8768.8	738.4	466.0	18.9

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Mo2020**		**Na5889**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	-2.2	3.2	1805.9	74.9
	300	1.2	0.3	2711.6	232.2
	350	0.9	0.4	3061.8	220.4
	400	0.8	0.4	3089.4	47.7
	450	1.6	1.2	2926.8	239.1
	500	1.4	0.9	3517.9	72.5
	550	2.8	4.3	3155.8	85.1
	600	1.1	0.9	2937.4	101.9
Corn	60	-2.5	1.3	467.5	43.1
	300	0.4	0.4	492.1	41.1
	350	0.8	0.3	854.2	113.6
	400	0.2	0.4	904.4	107.1
	450	1.0	1.2	1111.7	65.0
	500	0.0	0.7	1384.1	97.0
	550	0.9	1.3	778.1	136.8
	600	-0.8	0.2	1538.6	57.0
Dairy	60	-1.8	0.5	1617.6	72.2
	300	1.4	0.3	3270.0	26.8
	350	1.6	0.6	3698.3	62.3
	400	1.9	0.1	3568.5	42.5
	450	1.3	1.5	4008.6	77.9
	500	2.8	12.3	2223.1	105.3
	550	2.3	0.4	4424.5	103.6
	600	2.7	0.5	4538.0	67.7
Oak	60	-0.7	1.3	221.9	32.9
	300	1.3	0.3	297.0	35.2
	350	1.9	1.1	338.8	23.5
	400	0.2	0.9	320.7	45.5
	450	1.0	0.8	229.2	40.4
	500	-0.6	1.2	330.3	44.4
	550	0.8	0.4	277.2	52.8
	600	-0.6	1.1	51.7	17.2
Pine	60	-1.8	1.2	119.2	19.0
	300	-0.2	1.4	327.1	9.3
	350	1.1	1.8	134.3	5.6
	400	-0.7	0.7	351.0	22.9
	450	0.4	1.1	92.9	16.4
	500	0.2	0.6	331.5	24.4
	550	1.0	0.4	232.0	29.7
	600	-0.5	0.7	320.2	6.3
Poultry	60	-16.3	8.3	3778.2	70.0
	300	3.8	4.7	3868.0	284.1
	350	7.4	6.3	4218.1	105.8
	400	8.9	4.8	3208.5	91.0
	450	12.5	8.0	3694.7	185.5
	500	8.7	7.6	4537.4	66.7
	550	6.4	5.8	4048.2	674.2
	600	2.9	7.0	3457.2	452.4

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Ni2316**		**P_2149**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	-0.6	0.9	1142.0	55.3
	300	2.3	0.7	3013.6	481.9
	350	2.4	1.1	2644.3	99.8
	400	2.4	0.4	3118.7	48.3
	450	2.2	0.7	2508.0	45.2
	500	2.3	0.4	3114.9	107.8
	550	14.0	18.8	3063.8	187.3
	600	1.8	0.4	2952.5	56.0
Corn	60	-0.7	1.7	526.1	47.7
	300	10.4	3.1	1368.8	23.9
	350	1.0	1.2	1889.3	72.0
	400	2.0	1.3	1812.4	28.1
	450	3.0	2.7	2148.1	79.7
	500	1.7	1.3	1851.7	93.1
	550	2.2	0.4	2093.3	222.6
	600	2.2	0.4	2114.4	51.5
Dairy	60	0.8	0.5	762.1	74.2
	300	5.0	0.5	1152.1	165.7
	350	6.0	1.0	1809.8	53.0
	400	4.7	0.1	1466.5	124.7
	450	4.8	0.7	2001.0	58.7
	500	2.5	1.8	1754.2	165.8
	550	6.4	0.1	2358.3	225.3
	600	6.4	0.4	2433.4	17.9
Oak	60	-0.4	1.4	-28.0	2.1
	300	0.1	0.2	6.0	4.0
	350	9.1	10.0	11.1	13.3
	400	1.2	0.3	5.3	4.1
	450	1.5	0.5	42.8	35.9
	500	0.4	0.1	4.9	0.6
	550	1.2	0.7	29.3	16.4
	600	3.7	1.3	-47.0	29.2
Pine	60	1.4	0.4	-21.9	8.0
	300	0.9	0.2	255.2	64.6
	350	1.1	0.8	49.3	4.0
	400	1.7	1.0	34.8	5.7
	450	0.5	0.2	-1499.6	146.2
	500	0.3	0.2	1.1	22.4
	550	0.8	0.5	-7.6	0.6
	600	0.5	0.4	14.2	2.4
Poultry	60	0.8	10.2	16684.5	301.6
	300	13.4	7.0	26414.4	2075.4
	350	7.8	0.3	21256.2	978.2
	400	6.2	2.9	17957.3	1398.5
	450	8.0	2.5	17329.0	927.0
	500	17.3	1.3	30555.1	838.5
	550	11.8	2.0	20147.4	4715.4
	600	8.3	2.9	23595.6	3248.0

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Pb2203**		**S_1820**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	-14.9	9.3	570.4	31.7
	300	3.8	3.6	1102.3	48.6
	350	3.5	1.0	857.2	22.4
	400	5.0	1.5	859.4	5.9
	450	5.4	4.1	917.0	81.0
	500	1.1	0.8	928.2	27.3
	550	2.5	4.4	1018.7	13.9
	600	6.8	3.9	1022.8	7.2
Corn	60	-5.7	7.3	433.0	24.2
	300	1.7	11.2	697.5	6.2
	350	1.7	2.3	730.8	12.3
	400	1.1	3.2	712.1	20.8
	450	6.6	4.9	790.0	13.9
	500	-0.1	2.7	739.4	18.6
	550	3.8	1.8	731.4	38.4
	600	22.3	2.6	800.7	41.9
Dairy	60	-9.3	2.2	1044.7	58.0
	300	4.6	3.0	1798.8	58.4
	350	5.1	2.1	1600.9	72.4
	400	2.1	1.7	1484.1	50.2
	450	0.7	2.0	1608.4	87.8
	500	-9.8	31.0	1438.3	81.8
	550	0.1	1.3	1792.8	16.1
	600	2.2	2.7	1630.0	33.5
Oak	60	-1.4	9.0	10.0	1.8
	300	4.8	3.6	78.2	4.4
	350	20.7	8.3	182.3	77.2
	400	1.5	2.2	85.9	8.9
	450	8.0	6.9	74.3	2.1
	500	19.5	4.9	100.3	4.5
	550	5.5	4.6	99.7	5.8
	600	19.8	6.1	136.6	41.0
Pine	60	11.8	2.4	307.5	158.0
	300	2.7	3.8	113.7	2.2
	350	8.8	2.1	48.3	3.7
	400	7.3	2.5	103.0	8.4
	450	5.8	2.8	1692.1	121.7
	500	24.2	2.9	81.4	1.4
	550	36.5	10.0	237.5	295.7
	600	8.9	2.3	231.1	13.3
Poultry	60	-92.3	89.3	3425.5	111.1
	300	-27.5	30.6	4714.1	444.0
	350	9.7	30.5	3556.1	63.4
	400	-14.9	24.9	2983.4	190.3
	450	16.5	16.0	2897.9	162.6
	500	2.1	55.2	4593.0	107.2
	550	74.2	136.3	3231.2	651.7
	600	-29.1	25.6	3429.3	359.6

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Se1960**		**Si2881**	
		Mean	**SD**	**Mean**	**SD**
Bull	60	-6.7	2.0	39.7	39.2
	300	1.3	0.7	213.3	102.5
	350	-0.6	1.2	125.2	88.2
	400	1.0	1.0	239.3	183.4
	450	2.1	2.0	97.2	127.5
	500	0.9	2.6	613.5	152.8
	550	0.7	1.2	416.4	210.4
	600	0.7	2.0	145.6	102.3
Corn	60	-10.1	2.1	143.7	65.3
	300	-2.9	3.4	89.7	27.7
	350	-1.0	4.0	205.4	16.8
	400	0.4	0.9	363.9	62.3
	450	-0.1	2.9	252.7	38.1
	500	0.7	2.0	240.6	19.1
	550	2.1	1.8	335.4	104.6
	600	1.1	0.7	322.1	47.3
Dairy	60	-9.5	1.9	83.1	35.7
	300	3.4	2.6	115.5	24.0
	350	-0.6	2.3	154.3	36.8
	400	-0.1	2.6	111.6	29.8
	450	-0.8	2.4	189.7	28.7
	500	-0.6	8.2	-407.9	45.0
	550	0.8	2.1	349.9	141.6
	600	1.3	1.9	310.4	58.4
Oak	60	-7.5	3.6	-32.1	8.9
	300	0.2	1.5	5.4	6.5
	350	1.3	1.0	-16.6	11.6
	400	-1.8	1.6	3.6	0.0
	450	0.7	2.4	-16.6	8.3
	500	2.5	1.0	11.1	6.5
	550	0.8	1.6	-24.7	8.5
	600	0.4	1.3	-70.0	0.2
Pine	60	-5.4	1.9	-11.2	3.8
	300	1.2	1.3	21.6	3.1
	350	3.1	4.7	-22.2	7.1
	400	1.4	2.3	10.3	6.5
	450	1.8	1.6	-15.4	6.1
	500	0.8	3.5	-53.4	0.2
	550	0.4	0.8	-20.8	6.1
	600	0.6	0.4	-51.1	3.6
Poultry	60	-76.7	21.3	51.7	51.0
	300	-2.5	8.9	120.0	116.0
	350	-10.7	20.5	-58.7	41.3
	400	25.6	7.4	-209.5	0.2
	450	-0.9	11.1	-211.3	32.1
	500	-9.1	8.0	-206.5	149.1
	550	0.4	16.6	-39.6	118.6
	600	-12.9	8.7	-331.8	88.7

Table A2.1.6 / 1.S4. (Continued)

Feedstock	Temp (°C)	Sr4215		Ti3349	
		Mean	SD	Mean	SD
Bull	60	21.8	1.3	6.8	2.2
	300	46.8	1.2	79.8	9.1
	350	45.6	0.7	86.6	18.2
	400	52.2	0.9	42.0	6.8
	450	48.2	4.1	42.3	15.7
	500	55.4	6.6	46.0	5.7
	550	56.5	1.6	51.4	19.6
	600	51.3	0.4	26.8	4.8
Corn	60	14.3	1.5	4.1	4.0
	300	30.5	0.1	6.3	1.9
	350	31.4	0.2	16.6	1.1
	400	33.5	0.3	22.9	2.1
	450	39.0	0.1	19.2	5.1
	500	41.0	0.6	16.0	9.3
	550	45.2	0.3	11.3	3.1
	600	43.8	0.6	26.5	7.6
Dairy	60	21.5	1.2	7.4	1.7
	300	54.1	17.4	132.8	44.9
	350	48.7	8.4	33.5	13.0
	400	42.5	2.4	68.1	7.9
	450	57.8	9.7	35.6	12.7
	500	44.0	2.3	24.6	10.8
	550	59.9	2.0	55.5	4.7
	600	50.9	0.7	53.3	3.3
Oak	60	4.0	0.1	-0.4	0.8
	300	5.9	0.1	-0.3	0.9
	350	8.6	0.2	1.3	0.6
	400	8.5	0.1	-0.1	0.5
	450	8.8	0.0	1.8	2.0
	500	11.8	0.1	-1.0	0.9
	550	14.7	0.1	-0.8	0.8
	600	10.6	0.1	2.5	2.0
Pine	60	9.7	1.2	3.1	0.5
	300	5.7	0.5	27.3	18.2
	350	3.6	0.1	4.3	0.8
	400	4.5	0.8	3.8	1.5
	450	5.5	0.4	9.3	3.5
	500	8.0	0.1	-0.1	0.4
	550	6.1	0.0	-0.6	1.4
	600	4.9	0.1	6.8	2.5
Poultry	60	282.7	27.2	36.4	10.3
	300	259.8	20.9	37.8	26.8
	350	385.0	35.5	27.1	12.9
	400	485.4	25.8	13.1	2.4
	450	478.5	26.6	11.3	5.2
	500	343.5	22.6	13.7	6.9
	550	455.8	38.5	18.2	6.7
	600	436.1	52.9	7.5	5.8

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**V_2924** **Mean**	**SD**	**Y_3710** **Mean**	**SD**
Bull	60	0.7	0.5	0.3	0.1
	300	0.6	0.2	0.4	0.2
	350	1.1	0.3	0.4	0.0
	400	0.6	0.1	0.5	0.0
	450	0.5	0.2	0.3	0.1
	500	0.7	0.1	0.6	0.1
	550	0.8	0.1	0.5	0.1
	600	0.7	0.1	0.5	0.0
Corn	60	1.3	0.6	0.4	0.2
	300	2.1	0.1	0.6	0.0
	350	1.7	0.8	0.6	0.2
	400	2.1	0.2	0.5	0.0
	450	1.8	0.3	0.6	0.1
	500	2.9	0.3	0.8	0.0
	550	2.6	0.4	0.8	0.1
	600	3.1	0.6	0.7	0.1
Dairy	60	0.6	0.4	0.0	0.0
	300	0.4	0.0	0.1	0.0
	350	0.4	0.1	0.0	0.0
	400	1.2	1.5	0.3	0.4
	450	0.9	0.7	0.2	0.2
	500	1.3	1.4	-0.2	0.1
	550	1.1	0.3	0.2	0.1
	600	0.7	0.1	0.1	0.1
Oak	60	0.1	0.0	0.0	0.2
	300	0.0	0.0	0.0	0.0
	350	0.2	0.1	0.0	0.0
	400	0.2	0.1	0.0	0.0
	450	0.1	0.1	0.1	0.0
	500	0.0	0.1	0.0	0.0
	550	0.1	0.2	0.0	0.0
	600	0.2	0.2	0.0	0.0
Pine	60	0.2	0.5	0.0	0.1
	300	0.6	0.2	0.0	0.0
	350	-0.2	0.6	-0.1	0.2
	400	0.3	0.2	0.0	0.0
	450	0.1	0.1	0.0	0.0
	500	0.1	0.1	0.0	0.0
	550	0.1	0.1	0.0	0.1
	600	0.1	0.1	0.0	0.0
Poultry	60	9.8	0.4	1.6	0.6
	300	10.6	1.1	1.4	0.1
	350	9.1	0.7	1.2	0.3
	400	10.0	1.1	0.9	0.1
	450	7.5	0.8	1.2	0.2
	500	13.6	0.7	1.7	0.1
	550	9.2	2.1	1.1	0.1
	600	9.6	0.9	1.3	0.1

Table A2.1.6 / 1.S4. (Continued)

Feedstock	**Temp (°C)**	**Zn**	
		Mean	**SD**
Bull	60	65.8	3.5
	300	161.8	16.3
	350	133.0	3.5
	400	164.6	2.7
	450	138.3	6.3
	500	167.1	18.5
	550	319.5	283.5
	600	193.1	53.4
Corn	60	59.4	43.7
	300	131.8	30.9
	350	66.0	7.7
	400	48.9	0.9
	450	1654.7	2756.0
	500	72.2	16.2
	550	82.2	29.1
	600	69.9	3.8
Dairy	60	56.4	10.6
	300	90.0	10.3
	350	98.5	2.3
	400	87.5	2.8
	450	120.6	20.1
	500	79.9	8.1
	550	141.7	24.3
	600	114.4	2.7
Oak	60	47.4	44.9
	300	5.1	5.6
	350	109.0	78.0
	400	32.6	30.8
	450	23.0	12.2
	500	10.7	2.3
	550	15.1	10.9
	600	22.6	3.4
Pine	60	45.6	12.2
	300	22.8	2.0
	350	20.6	1.9
	400	65.9	8.7
	450	45.0	17.1
	500	44.5	7.7
	550	37.6	10.8
	600	60.0	2.5
Poultry	60	359.1	16.5
	300	514.6	40.5
	350	394.3	34.5
	400	351.5	8.8
	450	311.4	15.9
	500	601.0	7.4
	550	450.5	65.8
	600	594.5	199.5

APPENDIX 2.2

PRIMARY DATA FOR CHAPTER TWO

Table A2.2.1 Modified Kitchen Performance Test. C=chai, L=lunch, S=supper

Tanui	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	4.00	4.00	5.00	Child 0-14				
	Woman 15+	3.00	5.00	5.00	Woman 15+				
	Man 15-59	5.00	5.00	5.00	Man 15-59	18.00	26.00	2.00	
	Man 60+	1.00	1.00	1.00	Man 60+				
	Total People	13.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.45
	3.00	4.00	3.00		Child 0-14	12.00	16.00	15.00	
					Woman 15+	9.00	20.00	15.00	
					Man 15-59	33.00	46.00	17.00	
					Man 60+	3.00	4.00	3.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	48.60	73.20	38.90			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	12.11	34.05	10.88	**57.04**		Man 60+	0.80		

Table A2.2.1 (Continued)

Kiverenge	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	5.00	7.00	5.00	Child 0-14				
	Woman 15+	3.00	4.00	3.00	Woman 15+	1.00	1.00		
	Man 15-59	2.00	3.00	2.00	Man 15-59	2.00	2.00	2.00	
	Man 60+	1.00	1.00	1.00	Man 60+				
	Total People	11.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	2.70
	3.00	3.00	2.00		Child 0-14	15.00	28.00	15.00	
					Woman 15+	10.00	17.00	9.00	
					Man 15-59	8.00	14.00	8.00	
					Man 60+	3.00	4.00	3.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	25.90	44.80	25.10			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	6.45	20.84	7.02	**34.31**		Man 60+	0.80		

Table A2.2.1 (Continued)

Bulimo	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	9.00	9.00	9.00	Child 0-14				
	Woman 15+	4.00	4.00	4.00	Woman 15+	3.00	3.00	3.00	
	Man 15-59	3.00	3.00	3.00	Man 15-59	2.00	2.00	0.00	
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	16.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.98
	4.00	4.00	4.00		Child 0-14	27.00	36.00	27.00	
					Woman 15+	15.00	19.00	15.00	
					Man 15-59	11.00	14.00	9.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	36.50	47.20	34.50			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	9.09	21.95	9.65	**40.70**		Man 60+	0.80		

Table A2.2.1 (Continued)

Vilemba	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	3.00	7.00	3.00	Child 0-14				
	Woman 15+	4.00	5.00	4.00	Woman 15+	4.00	4.00		
	Man 15-59	1.00	1.00	1.00	Man 15-59	6.00	6.00	0.00	
	Man 60+	1.00	1.00	1.00	Man 60+				
	Total People	9.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.98
	4.00	4.00	4.00		Child 0-14	9.00	28.00	9.00	
					Woman 15+	16.00	24.00	12.00	
					Man 15-59	9.00	10.00	3.00	
					Man 60+	3.00	4.00	3.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	28.70	46.40	19.50			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	7.15	21.58	5.46	**34.19**		Man 60+	0.80		

Table A2.2.1 (Continued)

Rugut	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	2.00	2.00	2.00	Child 0-14				
	Woman 15+	1.00	1.00	1.00	Woman 15+				
	Man 15-59	3.00	3.00	3.00	Man 15-59				
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	6.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	4.97
	5.00	5.00	5.00		Child 0-14	6.00	8.00	6.00	
					Woman 15+	3.00	4.00	3.00	
					Man 15-59	9.00	12.00	9.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	14.40	19.20	14.40			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	3.59	8.93	4.03	**16.55**		Man 60+	0.80		

Table A2.2.1 (Continued)

Kosgei	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	4.00	4.00	4.00	Child 0-14				
	Woman 15+	1.00	1.00	1.00	Woman 15+				
	Man 15-59	1.00	1.00	1.00	Man 15-59				
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	6.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.98
	4.00	4.00	4.00		Child 0-14	12.00	16.00	12.00	
					Woman 15+	3.00	4.00	3.00	
					Man 15-59	3.00	4.00	3.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	11.40	15.20	11.40			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	2.84	7.07	3.19	**13.10**		Man 60+	0.80		

Table A2.2.1 (Continued)

Lagat	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	3.00	3.00	3.00	Child 0-14				
	Woman 15+	1.00	1.00	1.00	Woman 15+				
	Man 15-59	1.00	1.00	1.00	Man 15-59		5.00		
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	5.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	4.97
	5.00	5.00	5.00		Child 0-14	9.00	12.00	9.00	
					Woman 15+	3.00	4.00	3.00	
					Man 15-59	3.00	9.00	3.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period								
						Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	9.90	18.20	9.90			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	2.47	8.47	2.77	**13.70**		Man 60+	0.80		

Table A2.2.1 (Continued)

Agousei	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	4.00	4.00	4.00	Child 0-14				
	Woman 15+	2.00	2.00	2.00	Woman 15+	2.00	2.00	2.00	
	Man 15-59	1.00	1.00	3.00	Man 15-59				
	Man 60+	1.00	1.00	0.00	Man 60+				
	Total People	8.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	4.97
	5.00	5.00	5.00		Child 0-14	12.00	16.00	12.00	
					Woman 15+	8.00	10.00	8.00	
					Man 15-59	3.00	4.00	9.00	
					Man 60+	3.00	4.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	17.80	23.20	21.40			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	4.43	10.79	5.99	**21.21**		Man 60+	0.80		

Table A2.2.1 (Continued)

Moshi	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	9.00	9.00	9.00	Child 0-14				
	Woman 15+	2.00	2.00	2.00	Woman 15+	16.00	16.00		
	Man 15-59	2.00	2.00	2.00	Man 15-59	4.00	4.00		
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	13.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	4.97
	5.00	5.00	5.00		Child 0-14	27.00	36.00	27.00	
		*Assuming we arrived after L, 1st day.			Woman 15+	22.00	24.00	6.00	
					Man 15-59	10.00	12.00	6.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	41.10	49.20	24.30			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	10.24	22.88	6.80	**39.92**		Man 60+	0.80		

Table A2.2.1 (Continued)

Sore	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	7.00	7.00	7.00	Child 0-14				
	Woman 15+	4.00	4.00	4.00	Woman 15+				
	Man 15-59	2.00	2.00	2.00	Man 15-59				
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	13.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.98
	4.00	4.00	4.00		Child 0-14	21.00	28.00	21.00	
					Woman 15+	12.00	16.00	12.00	
					Man 15-59	6.00	8.00	6.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period								
						Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	26.10	34.80	26.10			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	6.50	16.19	7.30	**29.99**		Man 60+	0.80		

Table A2.2.1 (Continued)

Iminza	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	4.00	4.00	4.00	Child 0-14				
	Woman 15+	1.00	1.00	1.00	Woman 15+	2.00	3.00		
	Man 15-59	1.00	1.00	1.00	Man 15-59	18.00	26.00	2.00	
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	6.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.98
	4.00	4.00	4.00		Child 0-14	12.00	16.00	12.00	
					Woman 15+	5.00	7.00	3.00	
					Man 15-59	21.00	30.00	5.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period								
						Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	31.00	43.60	13.40			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	7.72	20.28	3.75	**31.75**		Man 60+	0.80		

Table A2.2.1 (Continued)

Rono	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	4.00	4.00	4.00	Child 0-14				
	Woman 15+	1.00	1.00	1.00	Woman 15+				
	Man 15-59	1.00	1.00	1.00	Man 15-59	1.00	1.00		
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	6.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.98
	4.00	4.00	4.00		Child 0-14	12.00	16.00	12.00	
					Woman 15+	3.00	4.00	3.00	
					Man 15-59	4.00	5.00	3.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	12.40	16.20	11.40			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	3.09	7.53	3.19	**13.81**		Man 60+	0.80		

Table A2.2.1 (Continued)

Inzira	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	2.00	2.00	2.00	Child 0-14				
	Woman 15+	3.00	3.00	3.00	Woman 15+	4.50	3.00		
	Man 15-59	4.00	4.00	4.00	Man 15-59	4.50	3.00		
	Man 60+	1.00	1.00	1.00	Man 60+				
	Total People	10.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.51
	4.00	3.00	4.00		Child 0-14	6.00	8.00	6.00	
					Woman 15+	13.50	15.00	9.00	
					Man 15-59	16.50	19.00	12.00	
					Man 60+	3.00	4.00	3.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	32.70	38.20	24.60			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	8.15	17.77	6.88	**32.80**		Man 60+	0.80		

Table A2.2.1 (Continued)

Masiwa	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	2.00	2.00	2.00	Child 0-14				
	Woman 15+	2.00	2.00	2.00	Woman 15+			1.00	
	Man 15-59	4.00	4.00	4.00	Man 15-59		4.00		
	Man 60+	1.00	1.00	1.00	Man 60+				
	Total People	9.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.26
	3.00	3.00	4.00		Child 0-14	6.00	8.00	6.00	
					Woman 15+	6.00	8.00	7.00	
					Man 15-59	12.00	20.00	12.00	
					Man 60+	3.00	4.00	3.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	22.20	33.60	23.00			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28	0.99		Man 15-59	1.00		
Total capita-days	5.53	15.63	6.43	**27.59**		Man 60+	0.80		

Table A2.2.1 (Continued)

Boyio	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	2.00	2.00	2.00	Child 0-14				
	Woman 15+	5.00	5.00	5.00	Woman 15+		6.00		
	Man 15-59	2.00	2.00	2.00	Man 15-59		2.00		
	Man 60+	1.00	1.00	1.00	Man 60+				
	Total People	10.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.98
	4.00	4.00	4.00		Child 0-14	6.00	8.00	6.00	
					Woman 15+	15.00	26.00	15.00	
					Man 15-59	6.00	10.00	6.00	
					Man 60+	3.00	4.00	3.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	23.40	38.00	23.40			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	5.83	17.67	6.55	**30.05**		Man 60+	0.80		

Table A2.2.1 (Continued)

Mugo	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	3.00	3.00	3.00	Child 0-14				
	Woman 15+	3.00	3.00	3.00	Woman 15+				
	Man 15-59	2.00	2.00	2.00	Man 15-59				
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	8.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	2.98
	3.00	3.00	3.00		Child 0-14	9.00	12.00	9.00	
					Woman 15+	9.00	12.00	9.00	
					Man 15-59	6.00	8.00	6.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	17.70	23.60	17.70			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	4.41	10.98	4.95	**20.34**		Man 60+	0.80		

Table A2.2.1 (Continued)

Nyetich	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	3.00	3.00	3.00	Child 0-14				
	Woman 15+	2.00	2.00	2.00	Woman 15+				
	Man 15-59	3.00	3.00	3.00	Man 15-59	1.00			
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	8.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	2.98
	3.00	3.00	3.00		Child 0-14	9.00	12.00	9.00	
					Woman 15+	6.00	8.00	6.00	
					Man 15-59	10.00	12.00	9.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	19.30	24.40	18.30			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	4.81	11.35	5.12	**21.28**		Man 60+	0.80		

Table A2.2.1 (Continued)

Kuto	Usually Present				Additional Present (total people-days)				
		C	L	S		C	L	S	
	Child 0-14	1.00	1.00	1.00	Child 0-14				
	Woman 15+	3.00	1.00	3.00	Woman 15+	3.00	3.00		
	Man 15-59	3.00	2.00	3.00	Man 15-59	6.00	6.00		
	Man 60+	0.00	0.00	0.00	Man 60+				
	Total People	7.00							
	Meals during msmt period				Total meals eaten during msmt period				Total days during msmt period
	C	L	S			C	L	S	3.51
	4.00	3.00	4.00		Child 0-14	3.00	4.00	3.00	
					Woman 15+	12.00	7.00	9.00	
					Man 15-59	15.00	14.00	9.00	
					Man 60+	0.00	0.00	0.00	
	Total capita-days per meal during measurement period					Weighting			
	C	L	S	Whole day		Child 0-14	0.50		
	26.10	21.60	17.70			Woman 15+	0.80		
Fraction of day	0.25	0.47	0.28			Man 15-59	1.00		
Total capita-days	6.50	10.05	4.95	**21.50**		Man 60+	0.80		

Table A2.2.2. Household Fuel Use Data (stoves [CH=Chepkube, 3-S=3-stone, I=Improved]; farm ID [#]; biomass typle [W=wood, C=corn stover, S=sawdust]; visit order [A/B])

									First Visit				Second Visit			
Farmer	Village	Biomass	Stoves in household							Sub-sample		On-farm wet mass		Sub-sample		On-farm wet mass
			CH	3-S	SD	I CH	I 3-S	Matt	ID	FW FIELD (g)	DW LAB (g)	BIOMASS (kg)	ID	FW FIELD (g)	DW LAB (g)	BIOMAS S (kg)
Tanui	Sik Sik	W	1						1WA	233	216.95	69.75	1WB	273	254	17.4
Tanui	Sik Sik	C	1						1CA	26	23.55	2	-	-	-	-
Kiverenge	Kichire	W		1	1				2WA	566	488.65	33.74	2WB	410.2	370.5	13.8
Kiverenge	Kichire	C		1	1				2CA	-	-	1.5	-	-	-	-
Kiverenge	Kichire	S		1	1				2SA	221	183.65	7.5	2SB	52.7	45.4	2.58
Bulimo	Chepsoui	W		1					3WA	154	123.65	112.6	3WB	167.15	157	13.6
Vilemba	Chepsoui	W		1					4WA	135	122.15	158	4WB	197	143.85	54.8
Vilemba	Chepsoui	C		1					4CA	61	41.4	3.75	-	-	-	-
Rugut	Koibem	W	1						5WA	253	225.05	51.2	5WB	404.85	360.8	8
Kosgei	Koibem	W	1						6WA	283	255.05	24.2	-	-	-	3.9
Kosgei	Koibem	C	1						6CA	157	130.05	1.4	-	-	-	0
Lagat	Koibem	W						1	7WA	228	209.3	41.2	7WB	327.55	291.75	18.6
Agousei	Koibem	W	1						8WA	222	168.55	64.4	8WB	371.75	312.15	13.7
Moshi	Kamulembe	W		1					9WA	77	68.45	76.8	9WB	133.8	119.75	4.8
Sore	Kamulembe	W			1	1			10WA	92	70.35	57.9	10WB	46.5	42.45	4.5
Sore	Kamulembe	C			1	1			10CA	34	26.75	4.2	-	-	-	0
Sore	Kamulembe	S			1	1			10SA	109	72.65	26.6	10SB	103.6	100.7	6.9
Iminza	Bonjoge	W	1						11WA	175	111	53.8	11WB	133.65	116	11.8
Rono	Bonjoge	W	1						12WA	416	280	99.5	12WB	251.65	210.8	67.7
Inzira	Kapkerer	W		1					13WA	186	165.15	89.9	13WB	213.8	191.55	56
Inzira	Kapkerer	C		1					13CA	106	57.85	4	13CB	52.8	48.05	2.7
Masiwa	Kapkerer	W	1						14WA	298	269.4	21.61	-	-	-	0
Boyio	Cheboite	W	1	1					15WA	145.75	131	92.4	15WB	177	155.45	3.5
Mugo	Cheboite	W	1						16WA	145.95	134.2	26.2	16WB	210.35	181.35	2.2
Mugo	Cheboite	C	1						16CA	99.15	63.35	4.6	-	-	-	-
Nyetich	Kiptrauswo	W						1	17WA	204.65	179.85	72.2	17WB	215.7	182.45	12.8
Kuto	Kiptrauswo	W	1						18WA	110.5	101.7	35.9	18WB	219	196.1	29.1
Musa	Kapsengere	No storage		1								No wood stored				
Lidonde	Kapsengere	No storage		1			1* (classified as 3-stone regular)					No wood stored				