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Climate Change Impact of Biochar Cook Stoves in Western Kenyan Farm Households: System Dynamics Model Analysis

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Supporting Information

ABSTRACT: Cook stoves that produce biochar as well as heat for cooking could help mitigate indoor air pollution from cooking fires and could enhance local soils, while their potential reductions in carbon (C) emissions and increases in soil C sequestration could offer access to C market financing. We use system dynamics modeling 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' climate change impacts to key parameters; and (iii) quantify the effects of different climate change impact accounting decisions. Simulated reductions in mean greenhouse gas (GHG) impact from a traditional, 3-stone cook stove baseline are 3.50 tCO_2e/household/year for the improved combustion stove and 3.69−4.33 tCO_2e/household/year for the pyrolytic stoves, of which biochar directly accounts for 26−42%. The magnitude of these reductions is about 2−5 times more sensitive to baseline wood fuel use and the fraction of nonrenewable biomass (fNRB) of off-farm wood that is used as fuel than to soil fertility improvement or stability of biochar. Improved cookstoves with higher wood demand are less sensitive to changes in baseline fuel use and rely on biochar for a greater proportion of their reductions.

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 C 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 C credits could help finance these projects, enabling their important nonclimate benefits as well.

To access C 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 newly developed technology, and have yet to be rigorously investigated for their climate change mitigation potential.[16−18]

Biochar is the C-rich material produced when biomass is heated under anoxic or oxygen-limited conditions (pyrolysis),[19] and can be used as a soil amendment to improve fertility in degraded soils when developed appropriately for a given system.[20] The term "biochar" is used here to distinguish the material from charcoal created for fuel, and to denote its particular application in C-sequestering and emission-reducing projects as a soil amendment.

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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 modeling 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.

METHODS

Modeled System. Our modeled system is a rural farm household in the highlands of western Kenya (see Figure S1 in Supporting Information (SI)). The region is characterized 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 observations by the researchers of 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 focus. 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]

Model Structure. We employed a system dynamics modeling 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. These 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 (e.g., village or region).

Our new model, Stove Impact on Climate Change Tool (SImpaCCT), consists of four interlinked modules: on-farm production, soil C, cook stove fuel use and emissions, and GHG impact (Figure S2). The term GHG impact is used to highlight the inclusion of changes in soil C and biochar C as well as differences in direct stove emissions.

Farm Production Module. The farm production module (Figure 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 C and nutrients to the soil.[28] Experimental results show that maize grain yield increases by an average of 116% as biochar is applied (ref 20 and unpublished data). The degree to which this response is shown increases as both the total biochar in the soil and farm age increase, the latter being a corollary to increasing soil degradation and positive crop response to biochar additions. (The farm production module is described more extensively in the SI).

Fuel Use and Stove Emissions Module. The fuel use and stove emissions module (Figure 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 modeled stoves are the traditional 3-stone cook stove, a biochar-producing pyrolytic cook stove, and another improved cook stove which is modeled 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 combustion stove, as modeled in SImpaCCT, would be analogous to other types of wood-fueled improved combustion cook stoves.

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 unpelletized sawdust, corn cobs, and corn stover as fuel, as compared to a 3-stone cook stove, normalized by mass of food cooked.[16] 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 S2) and the sensitivity to these assumptions is analyzed.

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.

Stove Emissions. For the improved combustion and 3-stone stoves, all C in fuel biomass is converted to C in emissions during combustion, wheras 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 among emissions of CO_2, CO, CH_4, particulate black C, and particulate white/clear/brown C, based on CO:CO_2 ratios and other products of incomplete combustion (PICs):CO ratios (as described in the SI). N_2O emissions are expected to be negligible[31,33] and are omitted.

Soil Carbon Module. The soil C module models the biochar and nonbiochar soil organic C (SOC) dynamics of the farm's maize plots. SOC is modeled in four pools: residue C on soil (which has a labile and recalcitrant fraction), free light SOC, intra-aggregate SOC, and organomineral SOC (Figure 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 adapt extant ones in order to represent black C as a separate fraction and to base pool types on measurable SOC fractions. The model was parametrized using the measured maize stover production data from 2004 to 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 Farm Production Module) is assumed to be left 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. If this were true to a substantial extent, it would be necessary to model the kitchen garden's plant growth and SOC dynamics and to alter the expected rate of application and consequential effects on the maize plots. Although scenarios where biochar is used for fuel rather than applied to soils or is diverted from the farm completely would need to be considered for certain systems, such investigation is beyond the scope of this paper. Biochar is modeled as being composed of two fractions: one labile (10−50%) and one recalcitrant (50−90%) fraction.[37,38] The labile fraction is integrated immediately into the free light SOC fraction, where it behaves as the nonbiochar SOC does, decaying and cycling relatively rapidly. The recalcitrant fraction of biochar decays very slowly, with a mean residence time (MRT) of 100 to 1000 years.

Data were not available on the SOC of the farm soils other than for maize fields, so SOC was not modeled for them. Thus, we do not model any significant changes to the soil C stocks for other plots as a result of their biomass being used as fuel. As changes to SOC in the maize plots contribute the least to total changes to GHG emissions, this assumption would likely not change our conclusions substantially.

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 3-stone cook stove) scenario and the improved cook stove scenario provides a relative 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.[5,12,39] 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 nonrenewable 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 nonrenewable biomass, fNRB) allows us to explore scenarios between these two extremes.

In SImpaCCT, the on-farm wood biomass and the nonmaize biomass produced on the farm are modeled as being sustainable (fNRB = 0), whereas the off-farm wood biomass is set initially at fNRB = 0.8 (predominantly 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 Policy Analysis.)

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, whereas for other 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).[40] 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 modeled stove emissions, as well as their status in the Kyoto Protocol are shown in Table S4.

Table 1. Model Parameter Variation for Sensitivity Analyses

parameter	modeled distribution (mean, SD)	sensitivity analysis range (default)
MRT for passive biochar C	normal (600, 275)	100−1000 years (600)
passive biochar C fraction	normal (0.8, 0.05)	0.5−0.9 (0.8)
greatest impact of biochar on maize yields	normal (2.16, 0.69)	0.7−2.3 times no-BC yield (2.16)
fraction of maize stover gathered	uniform between 0.25 and 0.75	0.25−0.75 (0.25)
baseline fuel use	normal (1.9, 1,1)	1.0−3.0 kg dry wood/capita/day (1.9)
fNRB off-farm wood	normal (0.8, 0.25)	0.0−1.0 (0.8)

The equations used in the GHG impact module are described in greater detail in the SI.

Model Scenarios. To explore the probable magnitude of the net GHG impact deviation from baseline, the outcomes were simulated for 100 years with model parameters representing a 30-year-old farm, while simultaneously varying the MRT of passive biochar, the fraction of passive biochar C, the impact of biochar on maize yields, the proportion of maize residues gathered, the baseline fuel use, and the fNRB of off-farm wood as described in the modeled distribution column of Table 1, for 200 simulations using the Latin hypercube sampling method. (More details on the parameter distributions are given in the SI.) A 30-year-old farm is around the median age of the studied farms, and would have been farmed long enough for substantial 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.

Sensitivity Analysis. We conducted sensitivity analyses on key parameters to explore how individual parameters influence system behavior over a given range. 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 0.8. One quarter of the maize stover is gathered for fuel and nonfuel 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 2.16 times the yields without biochar. These parameters are varied uniformly as shown in the sensitivity analysis range column of Table 1.

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.

RESULTS AND DISCUSSION

GHG Impact Deviation from Baseline. The simulated mean reductions in GHG impact over 100 years are 3.69 tCO_2e/household/year for the prototype pyrolytic stove, 4.33 tCO_2e/household/year for the refined pyrolytic stove, and 3.50 tCO_2e/household/year for the improved combustion stove (Figure 1). (A comparison of each of the sources of emissions reductions is shown in Figure S10.) All reductions achieved by the nonbiochar 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 make substantial contributions. We compared our values to those in Johnson et al.[5] for Kyoto emissions from improved 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 those of Johnson et al.,[5] but are 7−10% less than the 100-year values for the pyrolytic cook stoves. This somewhat smaller estimated impact is largely because the effect of biochar application on 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

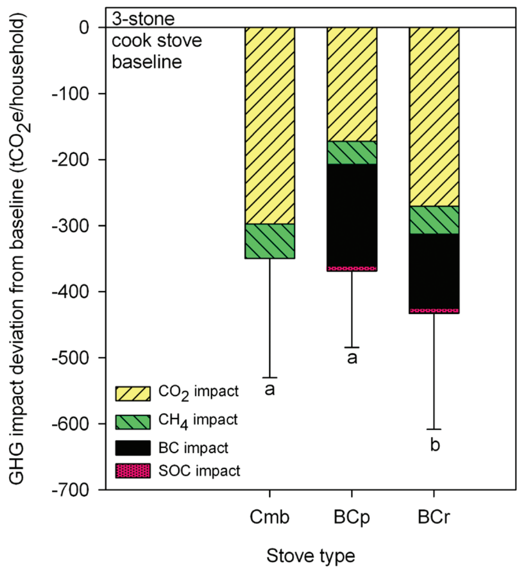

Figure 1. Simulated mean GHG impact deviation from baseline achieved after 100 years for the improved combustion stove (Cmb), the prototype biochar-producing stove (BCp), and the refined biochar-producing stove (BCr). Error bars show standard error of 200 simulations and letters indicate significant differences ($p < 0.05$, Tukey's HSD pairwise comparisons). The percentage of maize stover gathered, fNRB of off-farm wood, MRT of the stable fraction of biochar, passive fraction of biochar, impact of biochar on maize yields, and baseline fuel use were varied as described in Table 1.

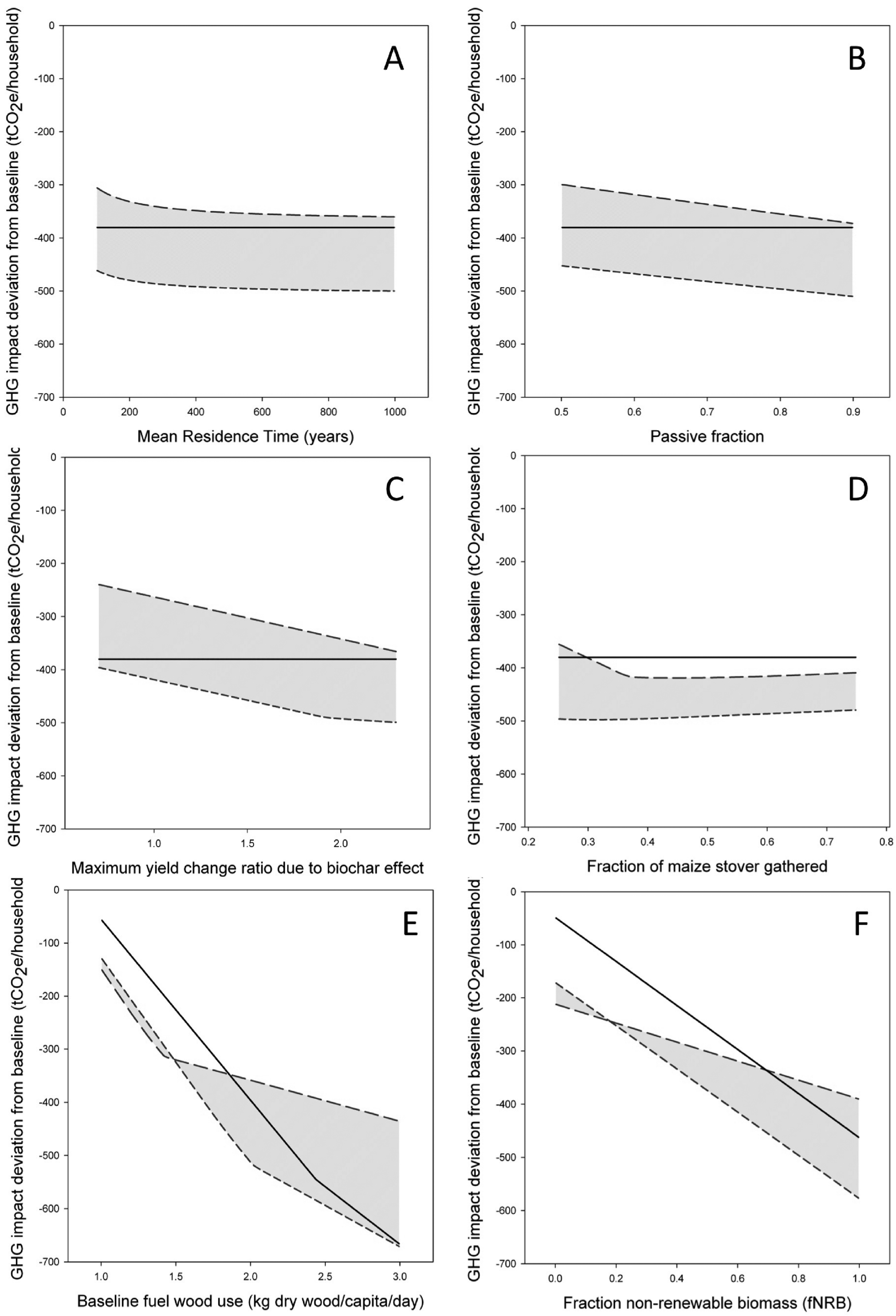

Figure 2. Simulated sensitivity of calculated GHG impact deviation from 3-stone stove baseline after 100 years when key parameters are varied. The prototype pyrolysis stove is represented by the long dashed line, the refined pyrolysis stove is the short dashed line, and the improved combustion stove is 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 biochar effect (0.7–2.3). (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 nonrenewable biomass from off-farm wood harvest (fNRB) (0.0–1.0). More negative values indicate greater GHG reductions. See SI for sensitivity analysis of varying initial farm age.

emission reductions by a mean of 28% for the refined biochar cook stove, and a mean of 44% for the prototype biochar cook stove, thus decreasing the economic viability of the project for biochar-producing cook stoves.

Sensitivity Analysis. Increasing the MRT of the passive fraction of biochar (Figure 2A) increases GHG impact deviation from baseline by 14% between 100 and 400 years, but only by 3% between 400 and 1000 years for the prototype biochar cookstove. As highlighted in previous research,[11,41] determining the precise MRT of biochar beyond a few hundred years is not as critical within this time scale as determining the passive fraction (Figure 2B), which increases GHG impact deviation from baseline by 18% 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.

The degree to which biochar impacts maize yields affects both SOC inputs from the crop and the amount of available renewable biomass, which, in turn, affects biochar and direct stove emissions accounting (Figure 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 and the expected yield increases did not occur (ratio = 1.0), emissions reductions would be 26% smaller for the prototype pyrolysis stove and 15% smaller for the refined pyrolysis stove, compared to the default ratio of 2.16. If yield were to decrease by 30% with BC application (ratio = 0.70), total emissions reductions are not substantially impacted, decreasing a further 7% (BCp) and 4% (BCr). However, food security concerns mean it would be essential to pair complementary biochars and soil types.[42] This could be challenging with cook stoves, for which biochar production is secondary to energy production, and which have fewer fine-tuning controls than industrial biochar systems and potentially highly variable feedstock inputs.

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.[43] The proportion of maize stover that is gathered (Figure 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 37% of biomass being gathered). Beyond this point, gathering more biomass results in relatively small gains. Above rates of gathering of 45% of maize stover for the prototype and 31% for the refined pyrolysis cook stove, 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 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 nonrenewable 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 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 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 degree of sensitivity similar to the combustion stove, but the less efficient prototype stove is ~56% 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 0.69, while the two biochar cook stove scenarios are equal at an fNRB of 0.18. 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.

Policy Analysis. Neither policy scenario had a substantial effect on GHG impact. Results for both analyses are discussed in detail in the SI.

Applications. The appropriate stove for a given area depends on what characteristics and impacts are most valued. Besides factors influential in adoption of stoves,[3,43] 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 modeling 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 substantial component of these reductions, if pyrolytic stoves are to access C 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, soil fertility, 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.

■ ASSOCIATED CONTENT

S Supporting Information. More detail on model development and evaluation and further simulation results. This material is available free of charge via the Internet at http://pubs.acs.org. An executable version of SImpaCCT is available from the authors and the Vensim Model Reader is available at http://www.vensim.com/reader.html.

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