DISSERTATION

THE DEVELOPMENT OF NUMERICAL TOOLS FOR CHARACTERIZING AND QUANTIFYING BIOMASS COOKSTOVE IMPACT

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ABSTRACT

THE DEVELOPMENT OF NUMERICAL TOOLS FOR CHARACTERIZING AND QUANTIFYING BIOMASS COOKSTOVE IMPACT

Biomass cookstove use can be damaging to both human health and the global climate. In an effort to minimize these impacts, numerous programs are working to disseminate improved biomass cookstoves. However, few programs have achieved extensive success towards improving either climate or health. One reason programs have only resulted in limited improvements has been the sector's inability to quantify cookstove performance.

A numeric tool has been developed for characterizing biomass cookstove performance. This dissertation documents the development of that tool. The document is comprised of three components: (i) the critical analysis of the uncertainty associated with current methods for cookstove field-testing, (ii) the development and validation of a probabilistic impact model for biomass cookstoves, and (iii) the application of these numerical tools to quantify cookstove impact.

Biomass cookstoves have traditionally been evaluated empirically. Cookstoves are tested in both the field and the laboratory, with each approach having advantages and limitations. Neither laboratory nor field testing are sufficient, however, for quantifying cookstove impact. Field-testing provides invaluable data on cookstove use but is limited by the large variability typically seen in the results. Drawing conclusions from field tests is challenging due to this variability. Many groups attempt to address testing variability by increasing the number of test replicates conducted. A numeric model was developed to determine the number of test replicates required to quantify cookstove performance in field settings.

Because of the large number of test replicates required to have statistical confidence in field-based data, an improved method of quantifying biomass cookstove performance is needed. Therefore, to address this need a probabilistic Monte Carlo prediction model was developed to quantify cookstove performance. The intention of the model is to serve as a tool for predicting the impact of various cookstove designs. The model integrates various facets of existing cookstove performance knowledge in more a cohesive fashion. Model simulations were compared to experimental studies to validate this approach.

Numeric tools are only valuable if they result in useful information; for example, information that allows informed decisions to be made. The potential of numeric models to provide valuable information for cookstove programs has been demonstrated by simulating the performance of multiple cookstove designs. Three improved cookstoves designs have been compared to a traditional three-stone fire. Each design was evaluated for multiple scenarios, use patterns, and locations. The impact of each design (in regard to climate and health) was then quantified and monetized. This exercise yielded two important findings. First, consideration of location and context is critical when comparing the performance of cookstoves. Second, numeric models can be used as highly informative tools to support decision-making in the cookstove sector.

Empirical testing is necessary for most technical programs; this is especially true for cookstoves projects. There are aspects of cookstove designs that can only be evaluated experimentally. Examples include whether an individual likes the cookstove, or if the design is appropriate for the specific cooking requirements of a particular community. Physical testing is needed to answer some basic questions such as: Do users find the cookstove intuitive to use? Do they like the color? However, empirical testing is not well-suited to answer every question related to cookstove performance. For example, comparing the climate impact of different cookstove designs is difficult in the field. The work presented demonstrates the potential of numerical models to provide invaluable information to the cookstove sector. The development and validation of these models has been documented. These models can help quantify the impact of current designs and help guide the development of future cookstove programs.

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1. Introduction

Nearly 3 billion people in the developing world cook on biomass-burning stoves that are little better than open fires (1, 2). This form of biomass combustion has numerous implications for both climate and health (1, 3, 4). However, despite the worldwide prevalence of cookstove use, the health and environmental impacts of biomass cookstoves are rarely quantified directly. There is a need, therefore, to improve our ability to predict biomass cookstove impact, in terms of both health and environmental effect. Stove performance data help define gaps and limitations, which, in turn drive innovation. Performance data also helps to determine whether an invention (e.g., the replacement of old, inefficient stoves with less polluting, fuel-efficient ones) would yield positive outcomes. New approaches of testing and evaluation are required if the 500–600 million improved cookstoves that are needed around the world are to be designed, manufactured, and distributed successfully.

A challenge many cookstove programs face is determining whether their efforts are having any positive impact. Evaluating the impact of a cookstove program is problematic, as technically robust methods of quantifying cookstove performance do not yet exist. Without the ability to measure performance, two critical questions for a successful cookstove program cannot be answered: (a) What does the program need from a cookstove (performance-wise) to be successful and (b) does this cookstove address the needs and goals of the program?

The goal of this work is to improve the sector's ability to characterize cookstove performance and predict the impact associated with cookstove interventions. To achieve this goal, the author has developed a numeric tool of quantifying biomass cookstove impact so that cookstoves, and cookstove programs, can be systematically evaluated.

1.1. Use of Biomass Cookstoves Internationally

In some regions of the world, 90% of the energy used is derived from biomass fuels, with one of the primary uses being domestic cooking (Figure 1). Examples of these biomass fuels include wood, agricultural waste, animal dung and charcoal. Although biomass fuels can theoretically provide carbon neutral energy, perfect conversion never occurs. All combustion, including biomass combustion in cookstoves, results in the release of products of incomplete combustion (PIC) including toxic gases and airborne particles. Between the PIC released and the prevalence of biomass cookstove use, stoves have become a major contributor to dangerous health and climate conditions internationally. For example, indoor air pollution from biomass fuel combustion is one of the leading causes of mortality and morbidity internationally (Figure 2) (6).

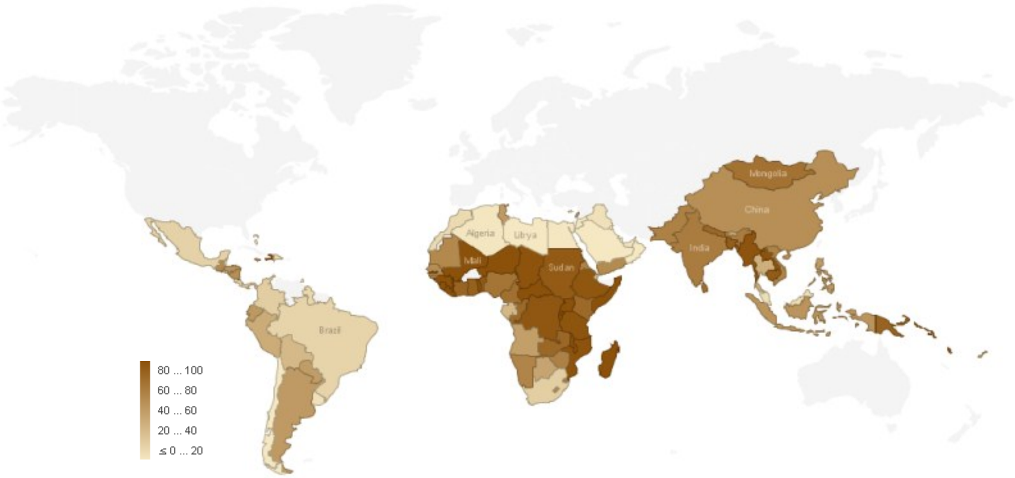

Figure 1: Estimated Percentage of Population Using Biomass as Primary Cooking Fuel. Map created from tabular data collected by the World Health Organization (1)

Indoor air pollution contributes to an estimated 2 million deaths annually (5). Although the precise burden of disease from biomass cookstove use is uncertain, a number of health impairments are known to be associated with exposure to the pollutants released during biomass combustion. The health concerns of indoor air pollution include those associated with the respiratory, cardiovascular and nervous systems (7, 8). For example, the World Health Organization (WHO) has shown that the inhalation of smoke from biomass combustion doubles the risk of respiratory diseases in children (7, 9).

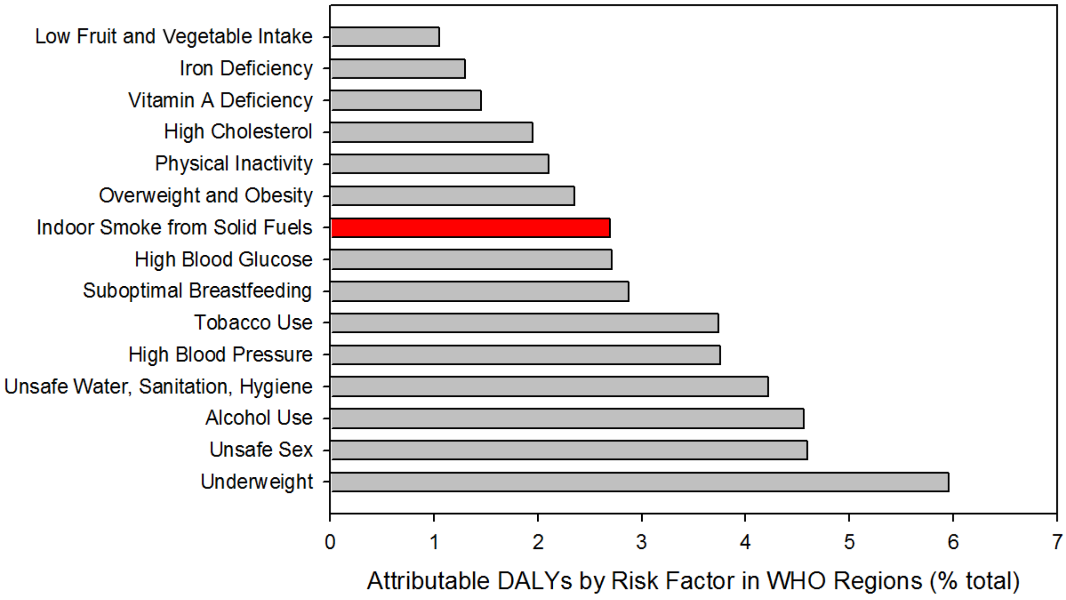

Figure 2: DALYs Attributed to Different Risk Factors. Plot created from image from data from the World Health Organization (6)

Women and children are at an increased risk of long-term health problems from indoor air pollution (IAP) due to the amount of time they spend in close proximity to cookstoves. Women spend as much as 90% of their time within 2 meters of the cookstove while preparing meals (10). Because of their high exposure to pollutants, women who use biomass cookstoves are at a significantly higher risk of having stillbirths as compared to women from similar populations who use gas cookstoves (11).

Many traditional biomass cookstoves have poor combustion and heat transfer efficiencies. The incomplete combustion and high fuel use of these stoves can have a large impact on the environment, both locally and globally. Wood cookstoves are thought to be responsible for an estimated 1–2% of annual global warming (12). The climate-forcing effect of a specific cookstove will depend on multiple factors, including how the fuel is sourced and the pollutants emitted, as each pollutant species has different global warming potential (GWP) (4, 12). Improving the combustion efficiency of biomass cookstoves could reduce their global warming impact by as much as 50% (12).

1.2. Previous Efforts to Disseminate Improved Cookstoves Internationally

Governments, non-government organizations, and private entities have all been working to improve biomass cookstoves since the 1970s (3). However, few improvements in either climate or health have been reported for many affected communities. Although quantifying cookstove sales can be challenging, an estimation of successful cookstove dissemination can be achieved by considering other metrics. Cookstove use has been found to increase lower respiratory infections (LRI) (5, 13), which is the second leading cause of death in children under the age of five (Figure 3) (14). Large-scale dissemination of clean cookstoves would be expected to trend with proportional reductions in LRI. To date, few countries have seen these reductions in LRI. As part of the United Nations Millennium Development Goals (MDG), data on child mortality rates exist for many countries. Based on UN data, only 38 of 137[1] countries categorized as “developing” (15) are anticipated to meet the 2015 MDG for reduced child mortality (Figure 4).

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[1] Likelihood of success estimated by projecting trends in child mortality between 2005 and 2010 out to 2015 and comparing against the goal of reducing child mortality by 2/3 from 1990

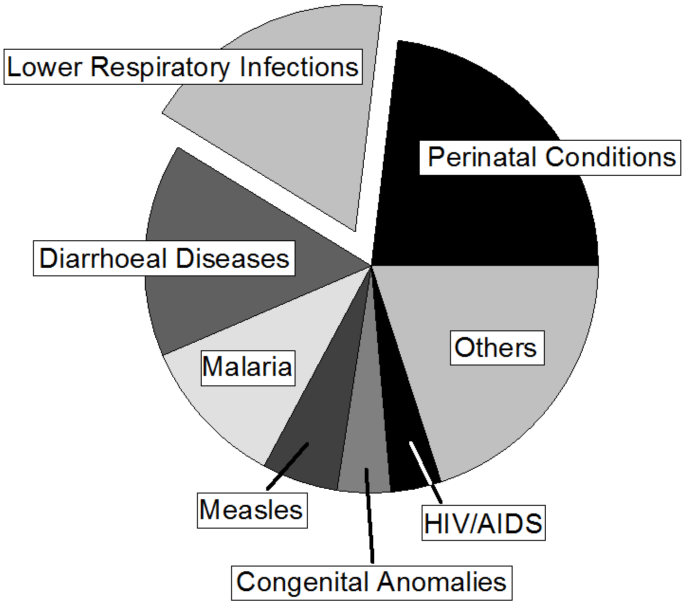

Figure 3: Leading Causes of Child Mortality Internationally (<5 yrs of age). Plot created using data collected by the World Health Organization (14)

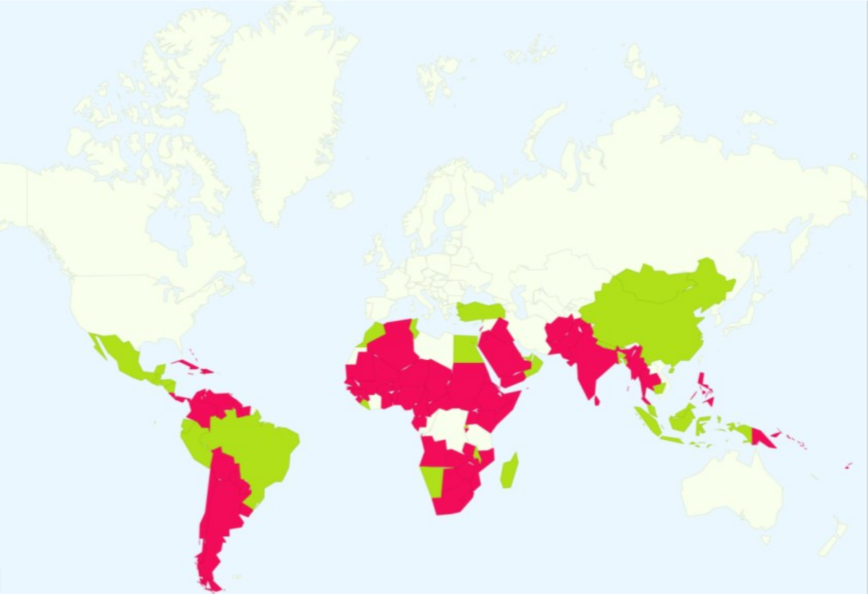

Figure 4: United National Millennium Development Goal Projections for Child Mortality for Select Countries[2]. Countries colored red are not anticipated to achieve the 2015 MDG guidelines. Map created using tabular data collected by the United Nations (15).

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[2] Based on trends from 2005 to 2010 continuing until 2015

1.3. Factors Affecting Biomass Cookstove Performance and Impact

Evaluating cookstove performance in the field is challenging due to the variability in cookstove emissions (and the resulting indoor air concentrations) between tests. Accurately quantifying cookstove performance (and making improvements based on these findings) requires methods that can handle highly disparate data. Many factors contribute to variability in biomass cookstove performance. Performance, in the context of this publication, refers to the amount of fuel used, the concentration of pollutants to which an individual is exposed, and the climate-forcing emissions associated with cookstove use. Aspects of cookstove design and manufacturing, in addition to external factors, also contribute to testing variability.

1.3.1. Where Cookstoves are Used

Many of the health risks of biomass cookstove use are associated with the concentration of pollutants to which an individual is exposed. Pollutant concentrations inside a home depend on both the size and air exchange rate of the room in which the cookstove is used. Thus, one cookstove will produce different pollutant concentrations (and corresponding health effects) in different homes.

Home size and design varies greatly around the world. A literature review of 13 counties found more than a four-fold variability in kitchen size and five-fold variability in air exchange rates in homes using biomass cookstoves (Figure 5) (16-29). Data from this review came from an examination of peer-reviewed journal articles and government publications.

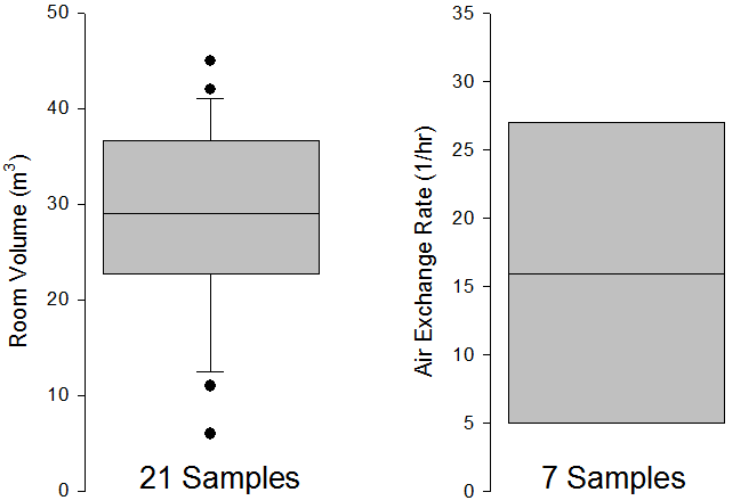

Figure 5: Compiled Results from Literature Review of Room Volumes and Air Exchange Rates (16-29)

1.3.2. How Cookstoves are Used

How a cookstove is used has a large impact on how the stove affects health and climate. For example, how a cookstove is used will depend on the meal being prepared. A major component of how a cookstove is used is the firepower at which the cookstove is operated. Firepower affects both how long pollutants are emitted, by changing heat transfer, as well as the quantity and composition of those pollutants (30, 31, 32). Operational firepower depends on the design of the cookstove, the meal being prepared, and other external factors (such as whether the mother is also watching a child or washing clothing while cooking).

1.3.3. Biomass Fuels Used for Cooking

The term "biomass" is a general term used for many different organic fuels. Although the term is convenient, it is overly generic. Many different "biomass" cooking fuels exist around the world and have a wide range of physical and chemical properties (Figure 6). Although some cookstove developers claim that their cookstove is suitable for multiple fuels, most cookstoves are designed to operate on a specific fuel type. All of the simulations conducted as part of this study assumed solid wood fuels were used; however, the modeling techniques developed here are also applicable to other biomass fuel types.

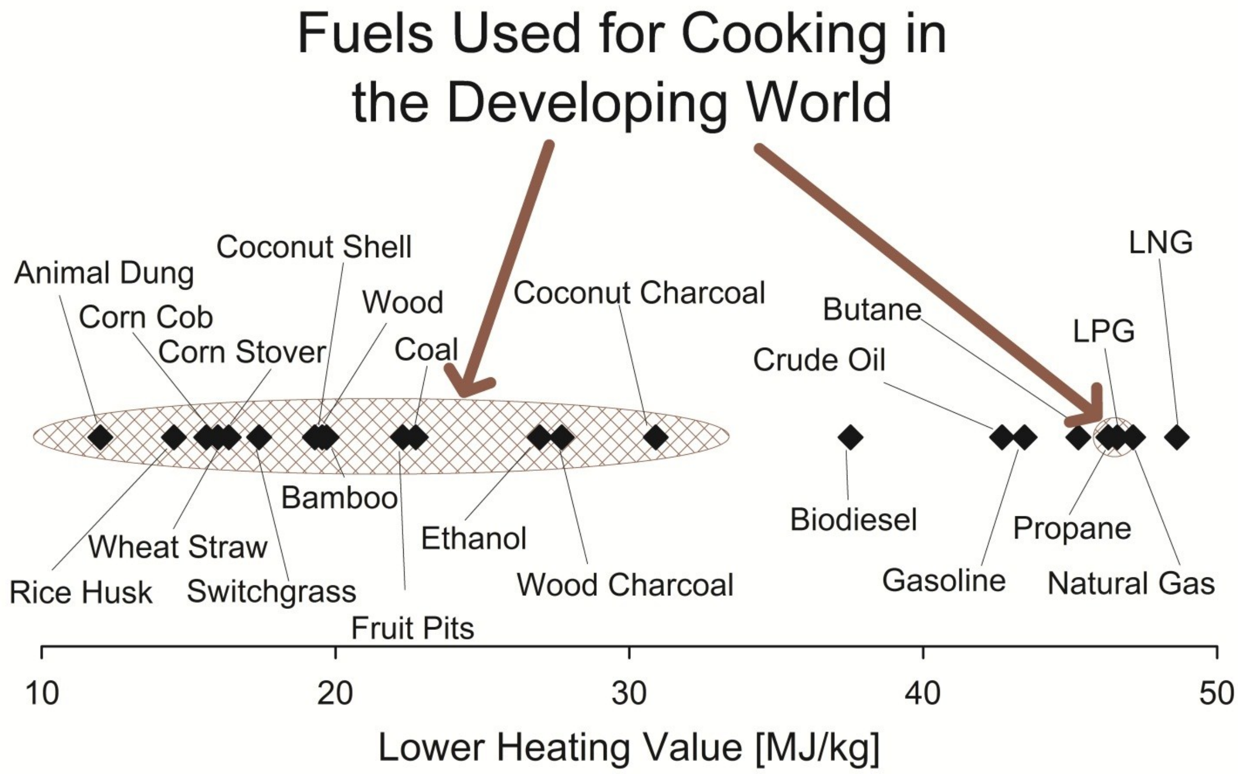

Figure 6: Fuel Heating Values (33, 34, 35, 36)

The most commonly used cooking fuel in the developing world is wood. Wood is the primary cooking fuel for an estimated 2.3 billion worldwide (Figure 7) (1), this accounts for 32% of the developing world's population and 71% of total biomass fuel users. Although wood is the most common fuel, "fuel stacking" is a common practice (37). Fuel stacking occurs when a home uses multiple fuel types on a regular basis. Fuel stacking occurs for a number of reasons. Some factors that affect what fuel is used include the meal to be cooked, the current availability of different fuels, and the finances currently available to the family (38). Each of these factors may experience seasonal (or even daily) variation.

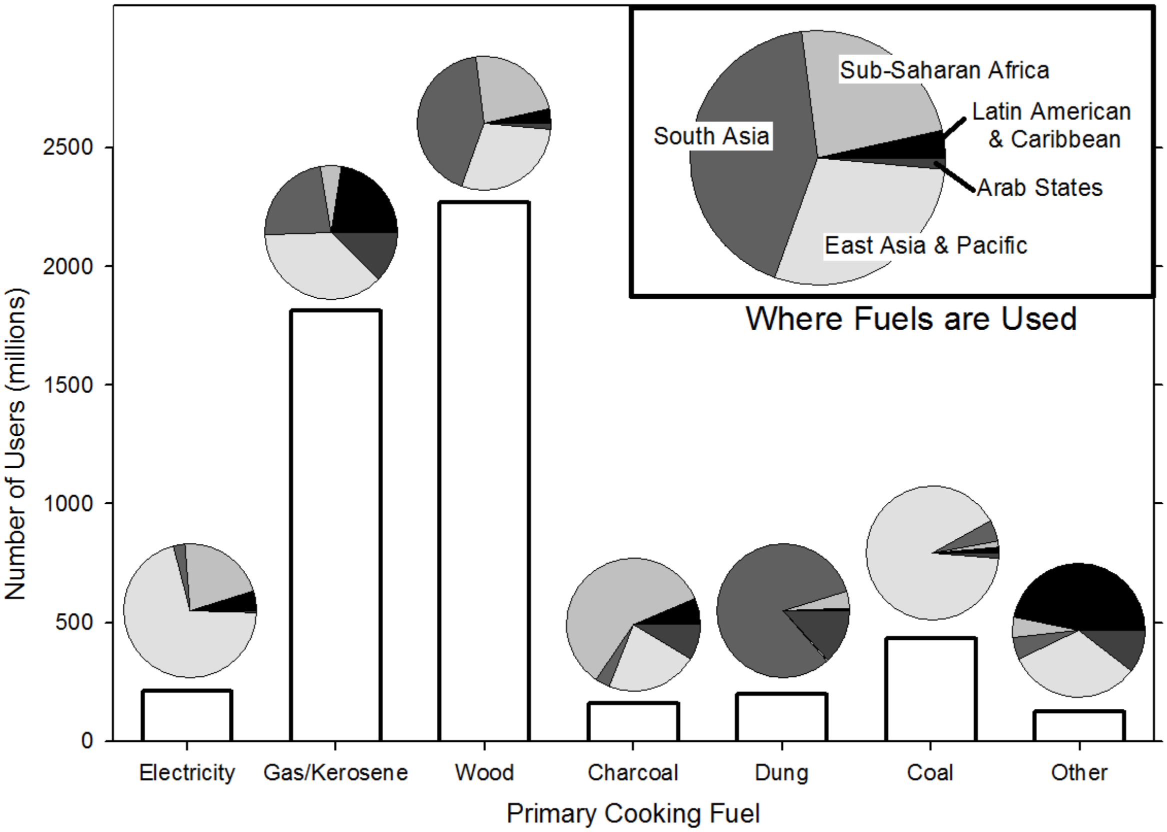

Figure 7: Cooking Fuels in the Developing World. Plot created from tabular data from the World Health Organization (1)

1.4. Previous Efforts to Model Biomass Cookstove Performance

Ideally, cookstove testing would always occur in real homes. However, the variability of the real world makes such testing impractical. Fully characterizing the performance and impacts of a cookstove design in the field would require an exorbitant number of tests. The range of home configurations, cooking habits, and fuel conditions that exist around the world makes the number of test replicates needed impractical. The global diversity of the "cookstove sector," therefore, requires the use of generalizations and idealizations. One approach of employing such generalizations is the use of numerical models.

Numerical models have previously been developed for biomass cookstoves (Table 1). These models have had a wide range of configurations and intentions. There have been models designed solely as a method of demonstrating a specific point; for example, the sensitivity of calculating net greenhouse gases (GHG) emissions based on estimates of renewable fuel fractions (39, 32). More detailed models have looked at specific case studies, such as comparing one cookstove program to another. Models have also been developed to illustrate the potential applications of numeric methods for evaluating biomass cookstoves (40, 41, 42) or as tools to interpret experimental data (25, 43). Few models have yet to be developed in the cookstove sector to serve as decision-making tools (44, 45).

Table 1: Overview of Key Publications on Cookstove Modeling

AUTHOR	YEAR	METRIC MODELED	MODEL OVERVIEW	REFERENCE
Johnson, M. et al.	‘11	Indoor air quality	Single-zone room model with variable room size and air exchange rate.	(40)
Whitman, T. et al.	‘11	Net GHG emissions	Critical analysis of non-renewable fuel fraction on net GHG emissions.	(39)
Jeuland, M. et al.	‘11	Impact assessment	Monte Carlo prediction models to quantify potential of unintended consequences.	(41)
Johnson, M. et al.	‘10	Total emissions	Critical analysis of carbon offset estimation methods.	(32)
Mink, T. et al.	‘10	Dissemination numbers	Method of predicting stove dissemination and adoption numbers by looking at socio-economic factors in the intended community.	(45)
McMracken, J. et al.	‘09	Health outcomes	Method of combining group exposure trends and individual intervention studies to improve the accuracy of long-term health outcome models.	(25)
Balakrishnan, K. et al.	‘04	Indoor air quality	Predictive air quality in homes using traditional cookstoves in India based on assumed emissions profile and range of home configurations.	(46)
Edwards, R. et al.	‘03	Total emissions	Assumption of linear relationship between combustion efficiency and emissions factors. Predicted reduction in emissions based on improvements in stove design.	(42)
Bazile, D. et al.	‘02	Fuel and monetary savings	Predicted savings based on baseline fuel use, efficiency improvement and fuel cost to predict impact.	(44)
Kishore, V. et al.	‘02	Dissemination numbers	Prediction of total stoves in use based on reported stove sales and estimated stove failure rates.	(43)

1.5. Combustion-Generated Pollutants

The chemical reactions that occur during combustion are extremely complex. Ideally, only CO_2, water, light and heat are produced during combustion. In practice, however, perfect combustion never occurs. Incomplete combustion results in the release of other compounds. Hundreds of chemical compounds have been identified in biomass combustion exhaust (47, 48). Many of these compounds have known detrimental impacts on health, the environment, or both.

1.5.1. Carbon Monoxide

One of the major products of incomplete combustion is carbon monoxide. When inhaled, carbon monoxide can bind with hemoglobin and reduce the body's ability to deliver oxygen to cells. The reaction between oxygen and hemoglobin forms carboxyhemoglobin (COHb); as COHb levels increase the body becomes oxygen-deprived, resulting in physiological and neurological problems. Carbon monoxide is most often associated with acute health effects, but this pollutant also has chronic health and climate-forcing effects (49).

Although the bond between CO and hemoglobin is temporary, COHb in the blood has a half-life of up to five hours (50). The long half-life of the bond means that the adverse effects of CO poisoning lasts long after an individual is no longer exposed (51). Oxygen deprivation affects numerous body systems causing both physical and psychological impairments. Death by asphyxiation is the greatest concern for acute exposure. Heart enlargement, increased blood cell count (52), and neurological impairments (49) (51) have all been linked to low levels of chronic CO exposure.

Carbon monoxide is a colorless, odorless and non-irritating gas making recognizing CO poisoning difficult (49) (51). Every individual reacts slightly differently to CO exposure, however, the American Lung Association (ALA) has published guidelines for identifying potential CO poisoning Table 2) (53). The build-up of COHb depends on CO concentration and exposure duration, as well as personal physiology (Figure 8).

Table 2: Symptoms of Carbon Monoxide Exposure

Approximate % COHb in Blood	Symptoms of Carbon Monoxide Poisoning
80	Death
60	Loss of consciousness, death if exposure continues
40	Disorientation
30	Headache, fatigue, impaired judgment
10	Loss of dexterity, diminished ability to learn

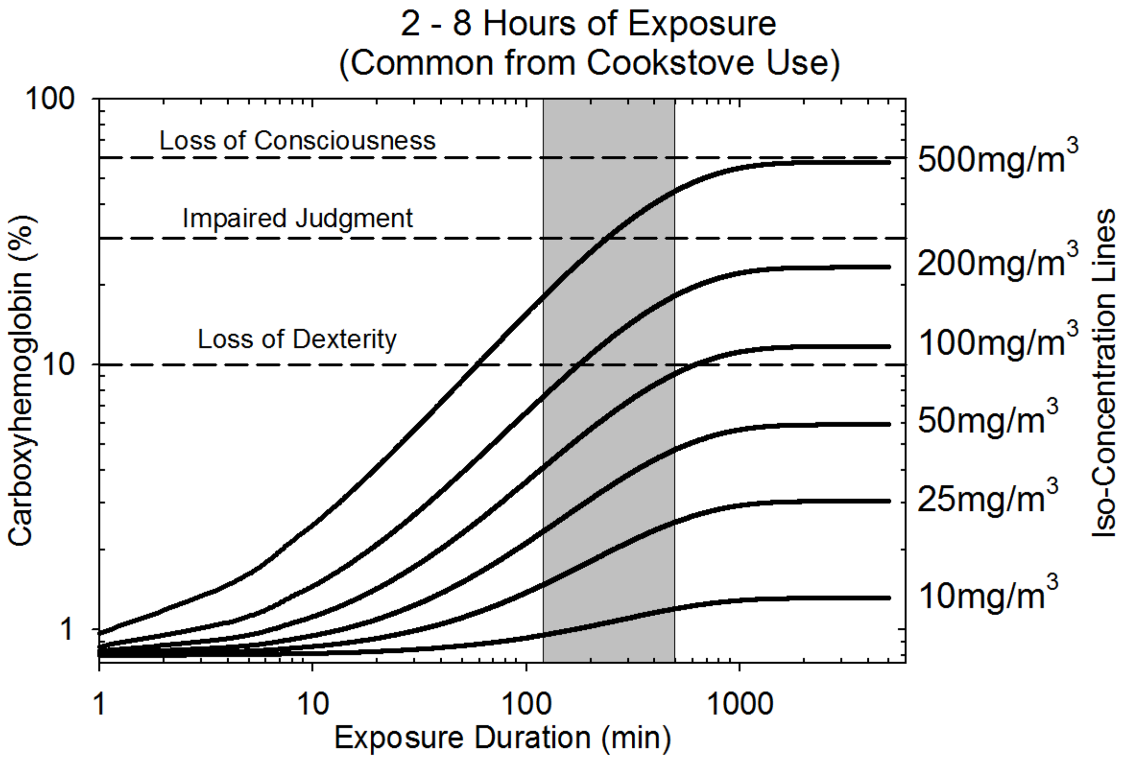

Figure 8: Carboxyhemoglobin Estimations for a Range of CO Concentrations Based on the Coburn-Forster-Kane Equation (53)

(54)

Table 3: WHO CO Exposure Guidelines (55)

Duration	Exposure Guidelines
15 minutes	100mg/m^3 (87ppm)
1 hour	35mg/m^3 (31ppm)
8 hours	10mg/m^3 (9ppm)
24 hours	7mg/m^3 (6ppm)

1.5.2. Particulate Matter

Particulate matter (PM) is released during the incomplete combustion of biomass fuels. Particulate matter consists of small solids or liquid droplets dispersed in the gas phase. These particles have both environmental and health implications. There is no safe level of PM exposure, however, the National Ambient Air Quality Standards (NAAQS provide guidelines for minimizing risk. The 1990 standard sets a maximum 24 hour average concentration of 150µg/m^3 for particles smaller than 10µm (PM_{10}) in diameter and an annual limit of 12 µg/m^3 for particles smaller than 2.5µm (PM_{10}) in diameter (56).

Exposure to particulate matter is known to have detrimental health effects. An increase of 20µg/m^3 to the average PM concentration of particles smaller than 10µm has been found to raise regional mortality rates by as much as 1% (18).Inhaled particulate matter is harmful to people of all ages but children are at an especially increased risk from exposure. The developing nature of children's bodies makes them particularly susceptible to long-term health repercussions from being exposed to PM (7). Indoor PM concentrations during cooking, a time when children are often present, can be 10 times higher than during other points in the day making them a susceptible population from the standpoint of both exposure and health effects (18).

The formation of particulate matter during combustion depends on many factors including flame temperature, the composition and concentration of combustion reactants, and residence time within the reaction zone (57) (58, 59, 60); all of these factors are cookstove specific. The destruction of particulate matter (once formed within the stove) is strongly dependent on gas composition and temperature (60) (61), which also depend on cookstove design.

Particulate matter can be classified in many ways. One common designation is the breakdown between elemental carbon (EC) and organic carbon (OC) content. Elemental carbon, also sometimes called black carbon or soot, is what is commonly associated with smoke. Elemental carbon is produced solely during the combustion, whereas, OC can be produced during combustion or formed in the atmosphere as part of secondary reactions that occur following combustion (62). The distinction between EC and OC is important when evaluating the environmental impacts of PM. Elemental carbon is thought to have a warming effect on the climate whereas OC is thought to have a cooling effect (63).

Particulate matter is also categorized by size. Three common distinctions are PM_{10} (particles less than 10 µm in diameter), $PM_{2.5}$ (particles less than 2.5 µm in diameter), and ultra-fine particles (particles less than 0.1 µm in diameter). These categories provide a convenient method of discussing PM as particulate matter size depends on the generation source and have different implications to climate and health (64).

1.5.3. Other Compounds of Concern

Carbon monoxide and particulate matter are the most commonly measured compounds in biomass combustion studies, but other toxic compounds and are undoubtedly present in biomass combustion emissions. Carbon monoxide and particulate matter are often used as proxies for other compounds not typically measured directly.

1.5.3.1. Hydrogen Cyanide

Hydrogen cyanide (HCN) is a colorless gas that is released from the incomplete combustion of biomass fuels. Both the Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) have set ambient HCN exposure limits of 10ppm or less. HCN can be absorbed either through direct contact with skin or by being inhaled. Exposure to HCN causes weakness, confusion, nausea and anxiety. As concentrations increase, HCN exposure can become lethal with death resulting from cellular asphyxiation (65). HCN and CO have been found to be lethal when mixed, even when at their individual sub-lethal concentrations. Although the interactions between CO and HCN in the body are not fully understood, studies have shown that the combined reaction rate of each compound with the body is greater than when each is alone (66).

1.5.3.2. Formaldehyde

Formaldehyde is a suspected carcinogen that is produced during combustion. Exposure limits of 0.75ppm have been set by OSHA but irritation begins at concentrations as low as 0.1ppm. The eyes, nose and throat are the first regions affected. Formaldehyde exposure is most commonly from inhalation or ingestion but can also be absorbed through the skin (67) (68).

1.5.3.3. Acetaldehyde

Acetaldehyde (C_2H_4O), released during biomass combustion, is a known irritant and probable carcinogen. More acetaldehyde is produced by stoves and fireplaces annually than any other source (69). Acetaldehyde is found at very low concentrations in ambient air, with eye and respiratory irritation in humans starting at concentrations of 25–50ppm. Acetaldehyde is considered a probable carcinogen, but sufficient studies have yet to be conducted to determine the level of risk (70) (69).

1.5.3.4. Nitric Oxide and Nitrogen Dioxide

Nitrogen oxides (NO_x) are formed during combustion, two of the most common being nitric oxide (NO) and nitrogen dioxide (NO_2). NO_x is an irritant and can be toxic at high concentrations. Acute NO_x exposure can lead to lung, eye and nose irritation and chronic exposure can lead to permanent lung damage and pulmonary edema (55).

1.5.3.5. Benzene

Benzene (C_6H_6) is a carcinogenic aromatic compound emitted from biomass combustion. Acute benzene exposure can be fatal and has been linked to a number of health concerns. Poisoning can occur from short-term exposure, which can lead to fatigue, headaches, dizziness, insomnia and nausea. Chronic exposure can result in a hampered immune system, leukemia, and blood disorders. There is no level of benzene exposure that is considered safe (55).

2. Numerical Evaluation of the Uncertainty Associated with Field Testing of Biomass Cookstoves[3]

2.1. Introduction

There is a world-wide need for improved biomass cookstoves due to the detrimental human health and environment effects of many traditional stove designs (6; 9; 13; 71). Collaborative efforts between organizations will be needed to address this global need. To help facilitate these collaborations, new testing protocols and standardized practices for sharing data have been adopted in recent years. One such effort is an International Workshop Agreement (IWA), an ISO document, developed for rating and comparing cookstoves (72). As part of the IWA, a resolution was passed to harmonize lab and field testing of cookstoves. The need for harmonizing lab and field testing was suggested partly to address the discrepancies often seen between the two approaches. These discrepancies have raised concerns regarding whether new cookstove designs are achieving their stated goals of improving health and climate.

As interpreted by the author, the goal of the IWA field-testing resolution is ensuring that the claimed benefits of improved cookstove designs, many of which have been designed in the laboratory, correspond to real world improvements. Comparing laboratory and field testing results, however, presents a number of challenges. One particular challenge is making statistically robust comparisons between laboratory and field-based data.

Determining the number of test replicates needed for adequate statistical power is important when designing a study. Sample size is strongly dependent on test variability. In this publication, variability refers to differences between repeated measurements. Comparing laboratory and field performance

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[3] The work presented in this chapter is based on the publication currently in preparation: L'Orange, C., DeFoort, M. Numerical Evaluation of the Uncertainty Associated with Field Testing of Biomass Cookstoves.

data will require sufficient replicates to engender confidence in the data. To predict the number of test replicates needed, a Monte Carlo prediction method has been used here. Using estimates of test variability, probabilistic simulations, were used to predict the number of test replicates required to compare a Tier 3 and a Tier 4 stove design (as defined by the IWA) in the field was calculated.

The feasibility of making laboratory vs. field comparisons is strongly influenced by the number of test replicates needed for adequate statistical power. The Monte Carlo model developed here was used to identify the dominant factors drive test-to-test variability. Understanding what factors lead to variability can help in the design of field studies so that the number of test replicates required can be minimized.

2.2. Factors Affecting Biomass Cookstove Performance

Designing a field study requires determining the number of test replicates to conduct. The number of test replicates required depends on test variability. Establishing an estimate for test variability requires having an understanding on what factors govern variability. By understanding the sources of variability, a program can determine which factors, if any, should be controlled. Which factors are controlled will depend on the goals of a particular cookstove program. A study looking at cookstove adoption would likely control very few factors. A study directly comparing the fuel efficiency of two stove types, on the other hand, might require more controlled testing.

Test variability depends on many factors. A degree of variability is inherent to field testing, although some source of y can be controlled (such as fuel size). Reducing test variability is challenging and requires determining the sources of variability. Although every cookstove program is unique, a few common sources of variability include the following:

- Stove Variability: Every cookstove produced is unique. Stove units of the same design will perform slightly differently from each other. Minor differences in cookstove construction can affect performance. Some variability exists between units even when standardized construction and quality control measures are used. The age and condition of a cookstove also affects performance.

- Fuel Variability: Biomass combustion is a complex process. Small differences in the condition or composition of fuel can have a large effect during combustion. Many fuel characteristics affect cookstove performance including volume, surface area, moisture content and fuel type/species (73).
- User Variability: The user has a large impact on the performance of a cookstove. An individual familiar with a particular cookstove will operate the cookstove differently than a first-time user (74, 75).
- Situational Variability: Situational variability encompasses many components including where a stove is tested. The concentration of pollutants that builds-up in a room will depend on the size and shape of the room and the amount of airflow through that room (76, 40).
- Measurement Error: Measurement error is different from the other categories discussed. Measurement errors do not directly cause variability; instead they are a sources of inaccuracy and imprecision. An inaccurate but consistent measurement will lead to bias in the results while not necessarily increasing testing variability. Measurement error includes both systematic and random errors. Random errors (in the context of measurement) would arise from poor instrument precision or variability in measurement readings. Increasing the number of samples taken can reduce random errors.

2.3. Simulating Cookstove Performance

The performance and variability of Tier 3 and Tier 4 cookstoves was simulated using a numeric model. The model used the sources of variability discussed above to estimate the concentration of carbon monoxide that resulted inside different homes using biomass cookstoves. An estimate of the number of test replicates required to have statistical confidence in the results was then calculated from these performance distributions.

2.3.1. Quantifying Variability in Biomass Cookstove Performance

The model is comprised of two sub-models used to estimated cookstove performance and two sub-models used to interpret those results (Figure 9) using a Monte Carlo framework. A Monte Carlo model is a prediction technique that uses a range of possible inputs to calculate the probability of different outcomes occurring. A Monte Carlo method was selected as it is well suited to using highly stochastic data and have been shown previously to work well for estimating cookstove performance (41, 40). Many references are available on the development of Monte Carlo methods. This model was developed using guidelines published by the US Environmental Protection Agency (77).

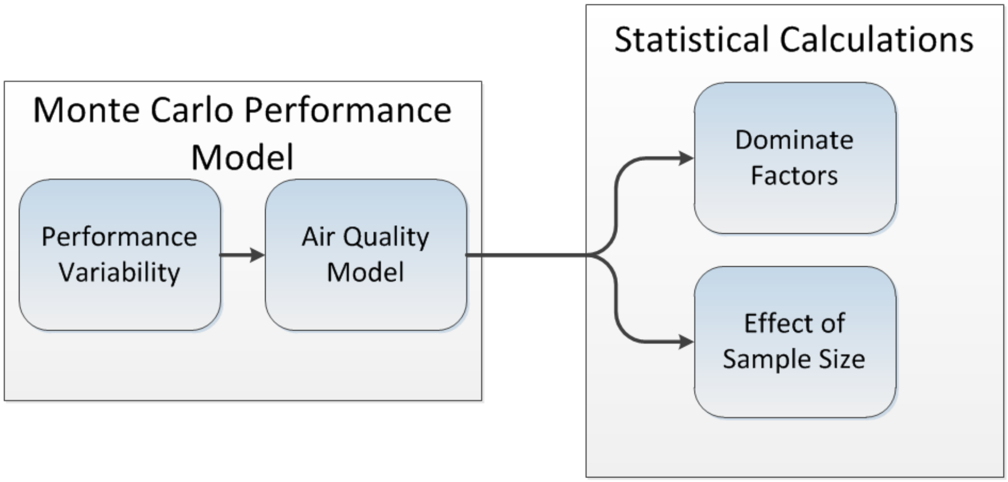


Figure 9: Schematic of Model Component Interactions

2.3.1.1. Estimating Performance Variability

Distributions that describe the varying rate of cookstove emissions were developed using three major sources of variability (Figure 10). Each stove Tier was assigned a fixed emission rate, taken from IWA tier guidelines (**Error! Reference source not found.**), and this rate was then broadened by accounting for sources of variability. The sources of variation considered include those associated with manufacturing, fuel type, and mode of operation.

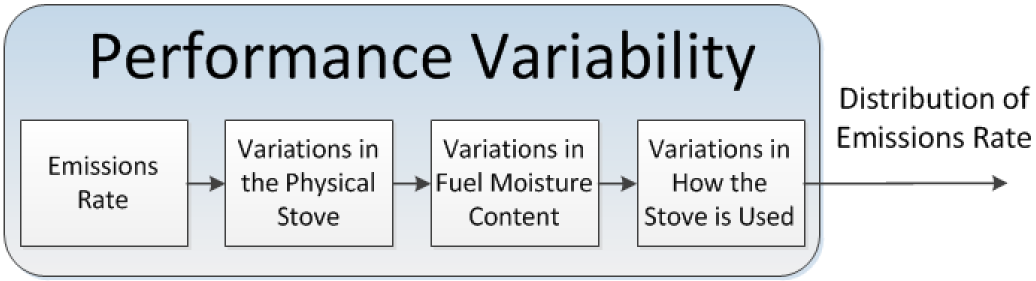


Figure 10: Schematic of Performance Variability Sub-Model

Table 4: Indoor Emissions Rates for Tier 3 and Tier 4 Cookstoves Air Quality Model

Tier Rating	Emissions Rate (g/min)
Tier 3	0.49
Tier 4	0.42

Room concentration estimates were developed using distributions of emission rates, room volumes and air exchange rates, respectively (Figure 11). Indoor air quality predictions came from a mass-balance, single-zone box model (see below). Box models require a number of assumptions including perfect and instantaneous mixing of the pollutants in a room, pollutants are not suspended after settling, and pollutant sources and sinks can be resolved in to single points. The model calculated steady state concentrations of carbon monoxide. Johnson et al. achieved good agreement between numeric models and experimental results using a similar approach (40).

$$\frac{dC_i}{dt} = \frac{\dot{m}_\imath(t) - Q(t) * C_i}{V}$$

Where:

$\dot{m}$: Emissions Rate of Pollutant i

V: Room Volume

Q: Air Exchange Rate

C: Concentration of Pollutant i in Room

t: Time

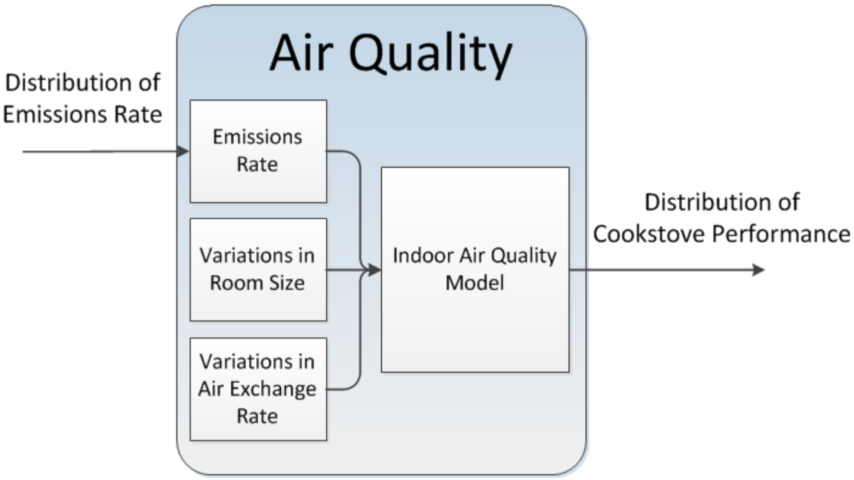
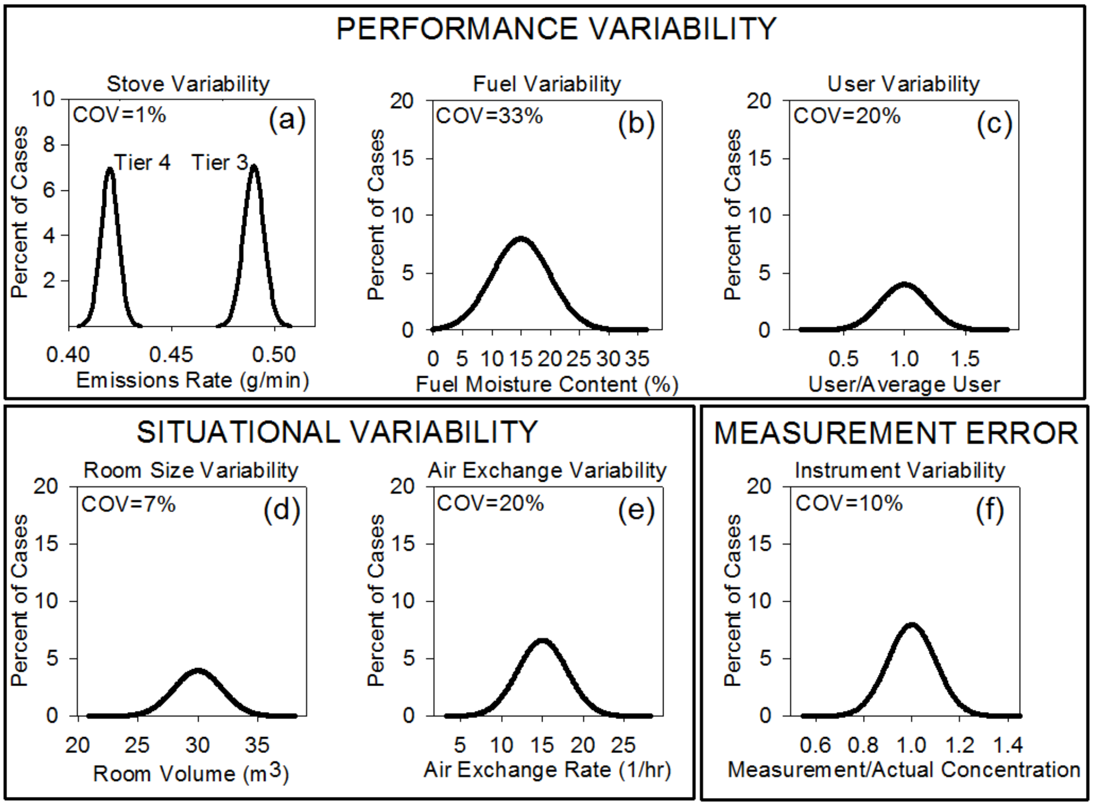


Figure 11: Schematic of Indoor Air Quality Model

2.3.1.2. Model Parameters

The Monte Carlo model included six input parameters (Figure 12). Distributions for these parameters were determined through a review of scholarly articles. The distributions are an estimation of real world variability. A simplification used in the model was that all input parameters had Gaussian distributions. Normal distributions have smaller standard deviations than other possible distributions and therefore results in the small number of required test replicates (78). In reality, many distributions do not have Gaussian distributions; however, a normal distribution was considered an appropriate starting point for the model.



Model Input Parameter	Model Inputs
Performance Variability	Tier 3: 0.49 g/min ± 0.005g/min Tier 4: 0.42g/min ± 0.004g/min
Fuel Moisture Variability	15% ± 5%
User Variability Adjustment Factor	1 ± 0.2
Room Size Variability	$30m^3 \pm 2.1m^3$
Air Exchange Rate Variability	15/hr ± 3/hr
Instrument Measurement Error Adjustment Factor	1 ± 0.1

Figure 12: Model Inputs Used. Distributions were Established for Each Major Model Parameter. Each parameter has been defined as a normal distribution.

Cookstove and Operator Variability

Cookstoves have inherent variability associated with their performance. This variability can occur for a number of reasons. For example, slight differences in cookstove construction or how an individual operates the stove may affect performance. Separating the relative contributions from these components is difficult. The model accounted for these components using two input parameters. The first parameter accounted for variability associated with the physical cookstove. Testing conducted by the US Environmental Protection Agency was used to establish an estimate for cooking variability from emissions rate variability of cookstoves in a highly controlled testing environment. Data from cookstove tests where the stove was carefully tended was considered (79, 80). Cookstove variability was estimated by looking at the most consistent tests the EPA was able to achieve. It should be noted that CO emissions rate variability fluctuated by more than an order of magnitude for different cookstove designs in the US EPA study and that the measurements include both variations in stove performance and some measurement variability. For this study, it was assumed that the EPA data had very little measurement variability due to the highly controlled testing environment These large fluctuations indicate that the parameters used here indicate only a best-case scenario; other cookstove designs may exhibit larger variability and thus require a larger sample size (80, 81).

The second parameter used to estimate cookstove variability was differences between users. Biomass cookstove performance depends strongly on how a stove is used; every individual will use a cookstove slightly differently. An estimation for variability between users came from comparing results from multiple laboratories. Each laboratory had independently operated a traditional three stone fire (80, 82). The standard deviation of these independent studies was used to estimate user variability.

Fuel Moisture Content Variability

Fuel conditions, such as moisture content, have a large influence on cookstove performance (73, 80, 83). Studies have demonstrated that emissions rates change with fuel moisture content (3, 83). Fuel moisture content depends on many factors including how long a fuel has been drying as well as ambient temperature and humidity. The distribution for the fuel parameter is based on equilibrium wood moisture contents for typical ambient temperatures and humidity (84). An emissions adjustment factor curve was calculated based on the moisture content distribution and a curve for the effect of moisture on emissions rates based on previous studies (3, 83) (Figure 13).

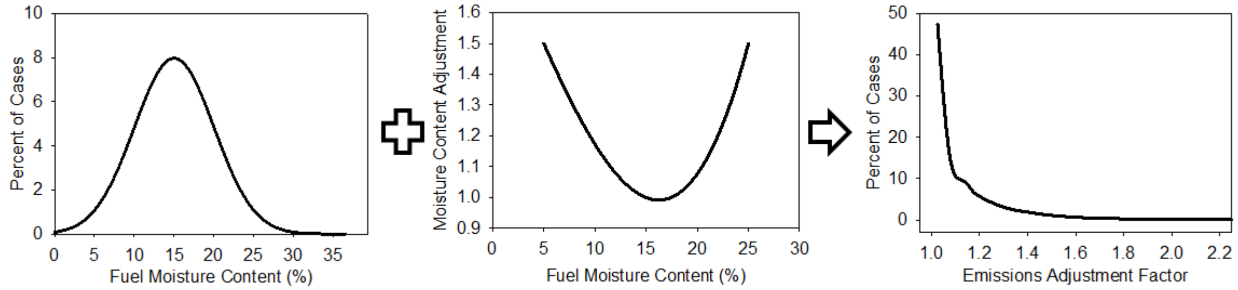


Figure 13: Emissions Rate Adjustment Factor Based on the Effects of Fuel Moisture Content on Emissions and a Distribution of Moisture Contents

Room Volume and Air Exchange Rate

The volume and air exchange rate of a room (or home) vary with climate and location. Representative room sizes and air exchange rates were established through a literature review (16- 29). A baseline room size and air exchange rate was defined by taking the average room size from multiple locations around the world. Room volume and air exchange rate input distributions were established by looking at the variability typically seen at any single location (19).

Measurement Error

All instruments have some uncertainty and error associated with them. Many factors can affect measurement error. Some of these factors include the quality of the instrument, how the instrument is operated, and how the instrument is maintained. The accuracy of the instrument can also depend on the magnitude of the reading. The model includes a conservative assumption that variability associated with measurement error was within 10% of the 'true value' for all concentration levels.

2.3.2. Calculating Required Sample Size

Given the input data presented above, the numerical model estimated the number of test replicates needed to distinguish the performance of a Tier 3 cookstove from a Tier 4 cookstoves in the field. Two sample sizes were calculated. The first simulation estimated the number of field tests needed to demonstrate that Tier 3 and Tier 4 cookstoves were statistically different based on room-level monitoring of CO concentration. The second simulation estimated the number of tests needed to have confidence that a sample mean is a close approximation of the true population mean for indoor CO concentrations.

Determining the number of replicates to prove statistical difference was done by calculating the p-value from an unpaired student's t-test. P-values were calculated for sample sizes ranging from three to 300 replicates per cookstove. Random tests were selected and the distributions at each sample size and p-values was calculated 100 times. The authors were looking for the sample size that had at least 80% of the calculated p-values under 0.05.

A similar process was used to determine the number of samples required to get an accurate measure of the population mean. For each distribution, the mean of the sample sizes ranging from three to 300 were calculated. One hundred random samples were selected at each sample size. These simulations were conducted to determine the sample size for which 80% of the sample means were within 5% of the true population mean. The selection of '80% power' was chosen based on classical statistical convention.

2.4. Results and Discussion

The Monte Carlo simulation approach revealed that, despite having distinctly different emissions rates, Tier 3 and Tier 4 cookstoves produced CO concentration distributions were quite similar (Figure 14). The considerable overlap in room-level CO concentrations resulted primarily from the combined effect of the different sources of variation considered. These results imply that although a very real difference exists between the two cookstoves, verifying that difference in the field will be extremely challenging.

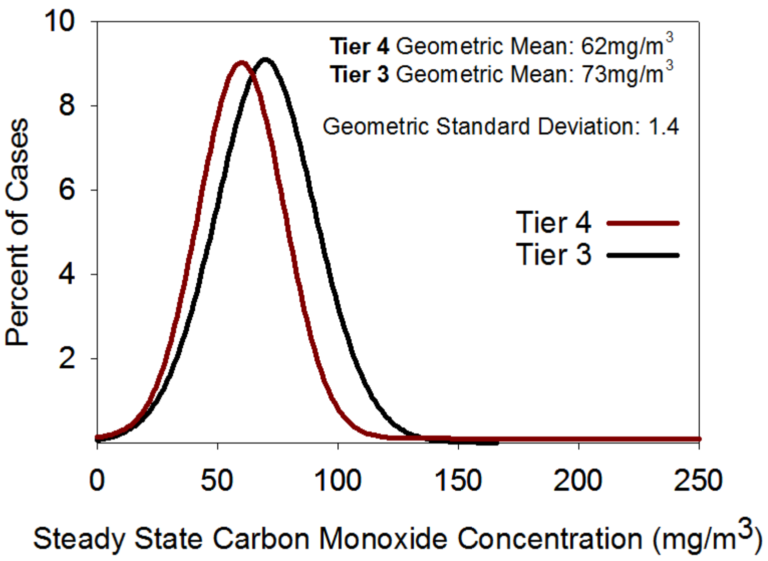


Figure 14: Steady State Concentrations Estimated for Tier 3 and Tier 4 Cookstoves Simulated from Theoretical Distributions of External Factors

2.4.1. Sample Size Required for Statistically Significant Results

A large number of test replicates is required to distinguish (statistically) the concentration distributions between Tier 3 and Tier 4 stoves because of the large degree of overlap that exists between them. The probability of finding a statistically significant difference between the two stoves for different sample sizes is shown in Figure 15. The model estimated that each cookstove would need to be tested approximately 51 times (a combined 102 tests for the two cookstove designs) to show, 80% of the time, that they are statistically different. These 102 combined tests would only demonstrate that the Tier 3 and Tier 4 cookstoves were different, not how they actually performed. If the testing were intended to quantify average indoor concentration of pollutants resulting from biomass cookstove use approximately 86 test replicates would be needed for *each* cookstove (for a total of 172 tests) (Figure 16). A 172 test replicates would be required to determine the average pollutant concentration to which an individual would be exposed. For many programs, a study design with 80% power would be unacceptable. Accordingly, achieving 95% power would require 128 test replicates to differentiate the two stoves and 180 test replicates per cookstove to quantify their mean concentration of pollutants resulting from the cookstoves.

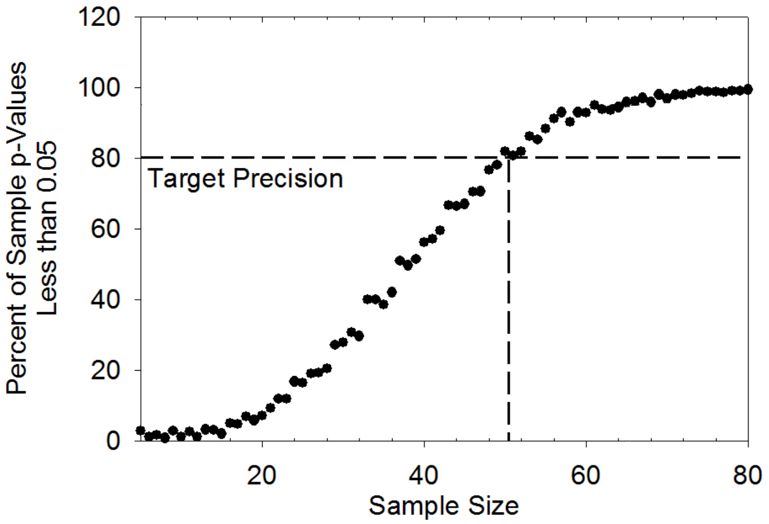


Figure 15: Study Power as a Function of Sample Size Required to Distinguish a Tier 4 from a Tier 3 Cookstove in the Field. Approximately 51 samples would be required for each of the two stoves (102 Samples Total) to achieve statistically significant differences in their measured means

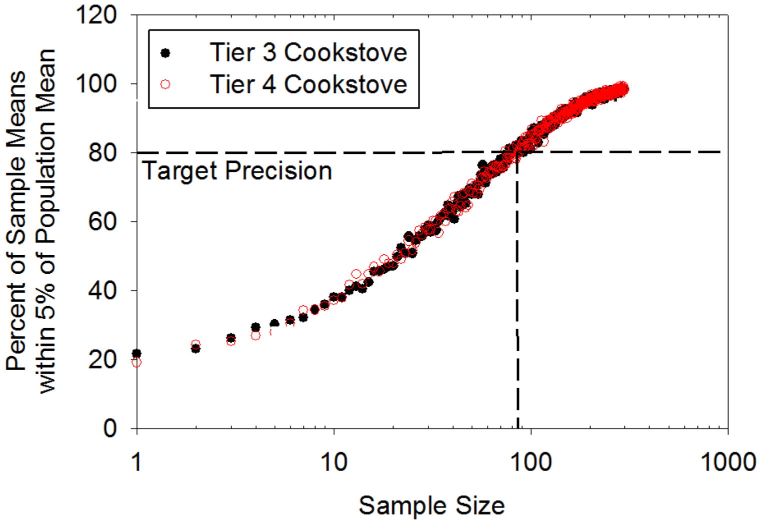


Figure 16: Sample Size Required for 80% of the Sample Means to be within 5% of the Population Mean. Approximately 86 test replicates would be required for both Tier 3 and Tier 4 cookstoves to have sample means within 5% of the population mean 80% of the time

2.4.2. Identifying Dominant Factors Affecting Performance Variability

For many programs, 200 test replicates would not be feasible in the field. Understanding the factors controlling field-testing variability can help cookstove projects design studies that required fewer test replicates. Regression plots have been used to identify the major sources of variability (Figure 17). For example, in the case modeled the dominate contributors to testing variability were fuel, air exchange rate and user variability. Addressing these components would have the greatest impact on reducing the number of test replicates required.

How testing variability is addressed depends on the specific goals of a program. A study designed to measure personal exposure may not control any testing parameters in order to accurately capture real world expose; this decision is made understanding a large sample size will be required. However, comparing the performance of two cookstoves under specific conditions would require controlling some testing parameters.

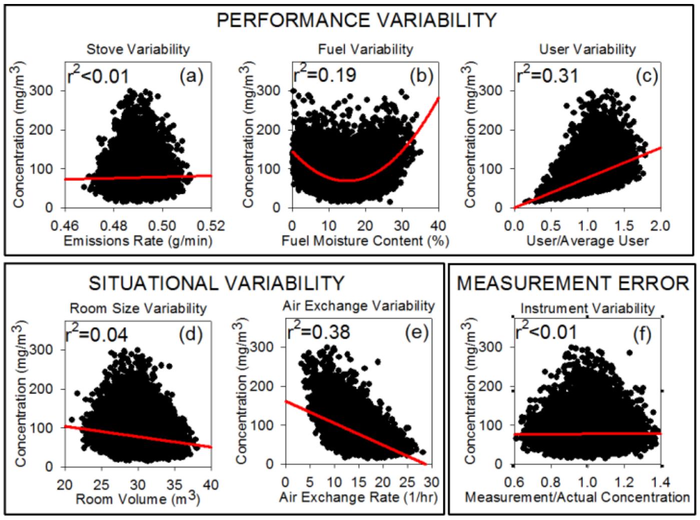


Figure 17: Correlation Between Steady State Concentrations and Select Sources of Variability. In all cases except (b) a linear correlation was assumed. A second order polynomial was fit to (b) due to the non-linear nature of the fuel moisture content correction factor used

It is interesting to note that although a model parameter might have large variability, it may not have a large impact on the overall performance distribution. For example, measurement error was highly variably (Figure 12f) but was only minor contributor overall performance variability (Figure 17f). This does not mean that instrument error is not important, only that a measurement error of 10% was only a small contributor to the overall system.

Instrumentation error is, however, critically important to quantifying the true populations mean. In the model considered here, the instrument was assumed to both over and under measure and that the error was the same at all concentrations. Neither of these is typically true. An instrument that systematically over or under estimates, or if the measurement error is concentration dependent, creates a bias in the results that can be difficult to detect when evaluating the experimental data.

2.5. Model Sensitivity to Input Parameters

A sensitivity study was conducted to evaluate the effect of specific input parameters on modeled CO concentration distributions (and resulting sample size calculations). For the purposes of investigating field testing feasibility, the range of performance (ie standard deviation) is more important than the mean. This is because the purpose of the study is to investigate model variability, not the resulting concentrations. Parameters were adjusted independently by increasing the standard deviation of each input distribution by 33%. Samples sizes were then recalculated.

Table 5: Sensitivity Analysis Used to Predict the Number of Test Replicates Required to Quantify Cookstove Performance

Model Input Parameter	Coefficient of Variation Used in Sensitivity Analysis	Increase in Sample Size Required to Quantify Cookstove Performance
Performance Variability	1.3	+2
Fuel Moisture Variability	44.0	+35
User Variability Adjustment Factor	26.7	+23
Room Size Variability	9.3	+5
Air Exchange Rate Variability	26.7	+21
Instrument Measurement Error Adjustment Factor	13.3	+8

The sensitivity analysis indicates that although model parameters affected the predicted sample size, the conclusions and trends remained valid (Table 5). As would be expected, the dominate variables that led to testing variability were also the parameters to which the model was most sensitive, for example fuel moisture content and air exchange rate. This suggests the need for being conservative when setting these parameters and using broad input distributions. Although the calculated sample size changed by approximately 30% in some cases, the number of test replicates that need to be conducted to have statistically significant results would still be impractical for many programs.

2.6. Conclusions

Testing cookstoves in the field is important; field testing provides helps to confirm that a project is having a positive impact in the world. However, field testing also has a number of major limitations. Many factors introduce variability into field measurements, which, in turn, clouds our ability to draw solid conclusions from these tests. Understanding the limitations associated with testing in the field requires an appreciation for the variability in test data.

A simplified case has been explored here to determine the number of test replicates needed to achieve informative data from field tests. The numerical model showed that even when using conservative values for input variability large numbers of test replicates were required for statistically significant results. Achieving the number of test replicates needed to quantify cookstove performance, especially when determining if two cookstoves produce different concentration levels, will be difficult for many cookstove programs.

Designing and conducting field tests with cookstoves is an extremely complex process. The challenges and limitations need to be understood before beginning a project. Although field testing is a critical component of a cookstoves program, the feasibility of using field testing to validate cookstove performance is questionable. If useful connections are to be made between laboratory and field testing, a more realistic view of variability, and the limitations of field testing, is needed in the cookstove sector.

3. A Monte Carlo Model for Evaluating Biomass Cookstove Impact[4]

3.1. Introduction

The impact (or success) of a cookstove program is rarely measured directly. Instead, programs measure performance metrics such as fuel consumption and pollutant emissions as proxies for impact. These metrics are also often used to evaluate whether a cookstove should be considered “improved”. However, the definition of ”improved cookstove” is vague and depends upon comparing one cookstove to another. For example, a cookstove may be considered “improved” because it produces fewer emissions, reduces fuel consumption, or simply costs less than some other design. These comparisons, however, are problematic as there is no universally accepted “reference” (or baseline) cookstove. How improved a cookstove is considered depends upon the cookstove technologies already available in a particular region. Because the success of cookstove programs is often predicated upon disseminating “improved cookstoves”, there is a need for methods of to quantify cookstove performance in terms of cost, emissions, and additional factors beyond the cookstove technology.

Emissions are often used as criteria for evaluating stove performance. Biomass cookstoves emit numerous harmful gases and aerosols that affect both human health and climate. Exposure to these pollutants depends upon the individual’s proximity to the cookstove, the fuel type used in the cookstove, the cookstove type, the room size, and the room ventilation rate. Cookstoves also affect the environment by releasing climate-forcing compounds (e.g., greenhouse gases and black carbon) and by contributing to deforestation. The climate effects from biomass cookstoves depend on factors such as the emissions released, the local geography, and the source of the fuel used. Determining if a cookstove is improved requires accounting for these factors, many of which are independent from the physical

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[4] The work presented in this chapter is based on the publication currently in preparation: L’Orange, C., DeFoort, M., Babbs, S. A Monte Carlo Prediction Model for Evaluating Biomass Cookstove Impact.

cookstove. Due to the variability of these factors, relying solely on empirical testing is impractical. Therefore, other methods of evaluating cookstove performance are required. Numeric models can provide a means to evaluate cookstoves performance (and impact) over a range of conditions in a manner that is practical in terms of both cost and time.

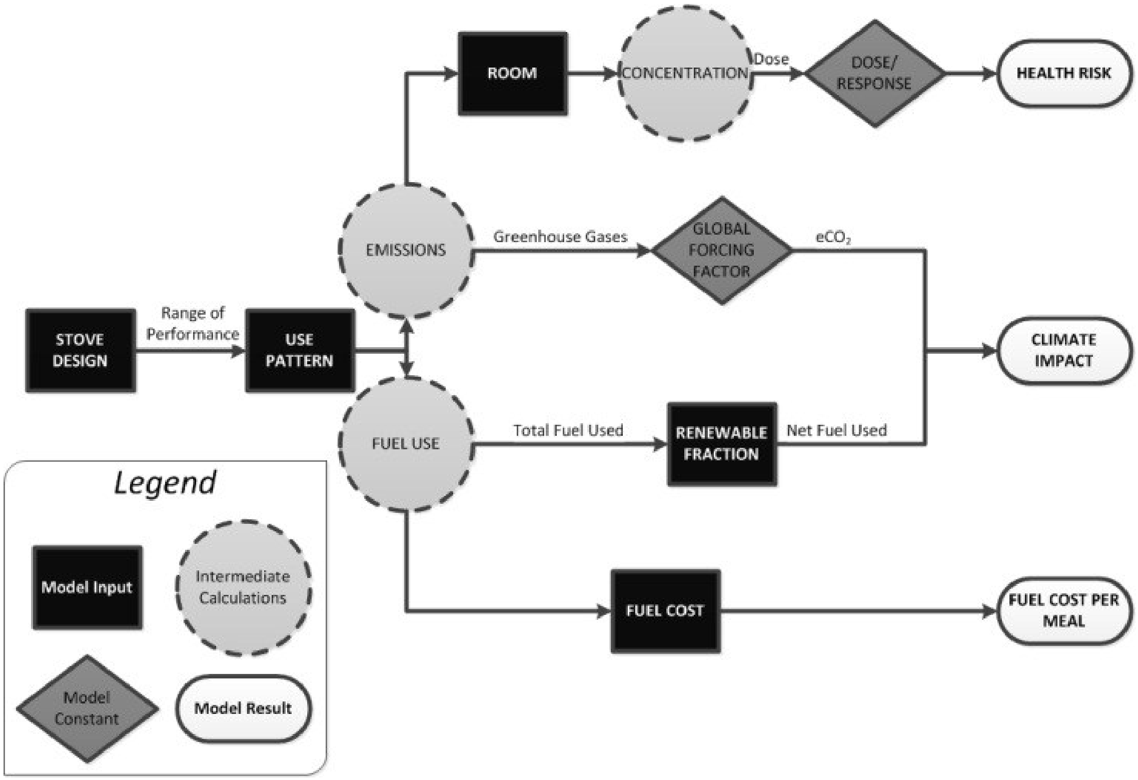

Figure 18: Outline of Components Needed to Understand the Impact of Cookstoves

3.2. Designing a Cookstove Performance Prediction Model

A probabilistic prediction model has been developed for quantifying biomass cookstove performance and impact. The model evaluates cookstove performance by simulating basic cookstove interactions (Figure 18). Health, climate, and monetary considerations of using biomass cookstoves are evaluated by considering a range of real world conditions and variables. A probabilistic forecast (or prediction) predicts the probability of different outcomes occurring. By calculating the cookstove performance over a range of conditions, instead of at a single point, a more comprehensive understanding of the impacts of a cookstove program is possible.

3.2.1. Introduction to the Monte Carlo Approach

A non-deterministic modeling method was used to capture the stochastic nature of biomass cookstove performance. Monte Carlo modeling is applicable to a wide range of situations such as modeling synaptic signaling in the brain (85) as well as economic planning (86). Monte Carlo simulations are comprised of three distinct elements. First, equations for basic interactions in the system are established, an example would be how emissions rate corresponds to the concentration of pollutants inside a home. Second, distributions are defined for key model parameters. An example of one such distribution would be the range of home sizes found in a particular community. Finally, the model runs iterative simulations, and for each iteration, random inputs are selected to calculate the probability of different outcomes occurring (Figure 19).

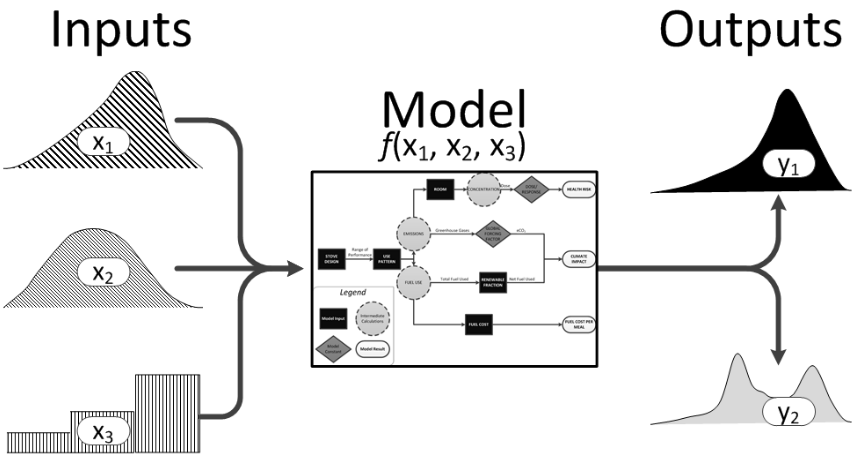

Figure 19: Basic Schematic of Monte Carlo Simulation Approach

Monte Carlo prediction models are well suited for situations that have highly variable and independent parameters, such as biomass cookstove performance. An added benefit of probabilistic simulations is determining which of these parameters has the largest impact on performance.

Understanding what factors affect performance can help programs determine where resources should be leveraged. For example, a cookstove program manager might question whether money be allocated for supporting design improvements or user education? More detailed explanations of Monte Carlo model design and implementation can be found elsewhere (77, 87, 88).

3.2.1.1. Interpreting Monte Carlo Simulation Results

Understanding the limitations of a Monte Carlo model, as is the case for all models, is important when interpreting simulation results. Monte Carlo models produce data, not information. An expert is needed to interpret simulation results because multiple questions could be answered from one model. For example, data from a Monte Carlo simulation could be used to evaluate the climate impact of a cookstove or to estimate precision associated with performance testing in the field. Interpretation of Monte Carlo simulation results also requires an understanding of model output (mean values vs. dispersion or variability). If the goal was to quantify the climate impacts of a cookstove design, knowing the average eCO_2 emitted from the stoves may be sufficient. Predicting the performance of a stove, on the other hand, is a very different question. In that case, mean values may be less informative as compared to estimates of variance. A narrow distribution indicates that the given situation has been well characterized, a broad distribution may indicate that more information is needed before programmatic decisions can be made. Numerical simulation models are well suited to help answer such programmatic questions, provided the data is interpreted correctly.

3.2.2. Model Framework

The model is comprised of a series of sub-components used to predict cookstove impact (Figure 20). These model components generate estimates of cookstove performance (in terms of health, climate, and operation costs) based on five categories of user input. Inputs in each category include an uncertainty term used to simulate a distribution of input values that mimic real-world variability. Each input category is targeted toward a specific aspect of biomass cookstove use/performance. These inputs are described in brief below.

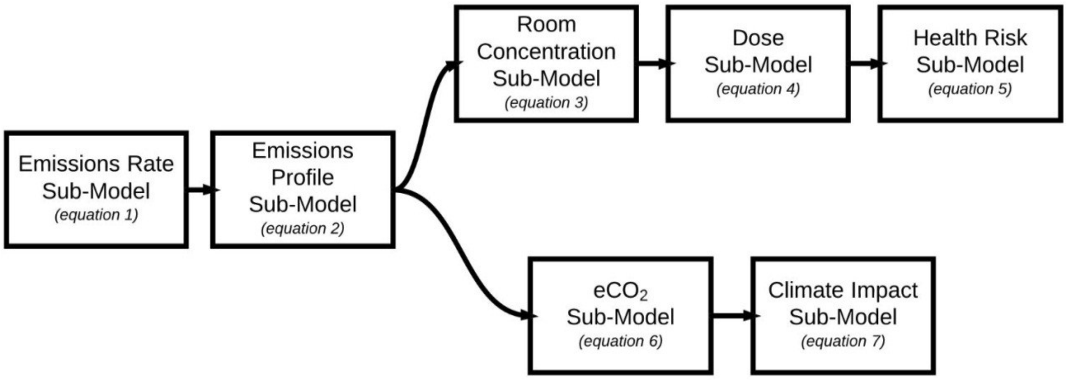

Figure 20: Interaction of Sub-Components Used in Impact Prediction Model

- Use Pattern: how is the cookstove used? Regionally specific cooking habits can be defined through a simplified use pattern; for example, how much time is spent boiling water or simmering? For the simulations tested here, cookstove use has been simplified into three operating conditions. The cookstove can be either off, operating at low power, or operating at high power.

- Stove Performance: what is the emissions rate of the cookstove? Cookstove performance is defined as the rate of emissions released, which is related to how quickly fuel is being used.

- Room Conditions: where is the cookstove used? Where a cookstove is used has a large impact on pollutant concentrations. The size of the home/kitchen in which the cookstove is to be used and the anticipated air exchange rate in that room are considered.

- Renewable Fraction: where does the fuel come from? The climate impact of biomass cookstove use depends not only on the performance of the stove but also on the fuel source. Sustainably gathered fuel has different climate implications than fuel coming by clear cutting.

- Fuel Cost: how much does fuel cost? For many families living in the developing world, fuel costs account for a major part of their weekly budget. The monetary benefit of using a cookstove that is more fuel-efficient is directly related to the price of fuel.

3.2.2.1. Relating Cookstove Design to Emissions Rate

Many factors influence the rate of emissions from a biomass cookstove. Detailed studies have shown that cookstove emissions can be predicted for a given cookstove geometry by knowing how the cookstove is being operated (30, 31, 32). Variations in cookstove operating condition could explain some of the discrepancies seen between laboratory and field studies for cookstove emissions performance (74, 63). The model used here defines pollutant emissions rates of a given stove (Equation 1) as a function of stove firepower.

Equation 1: Cookstove Emissions Rate as a Function of Firepower and Fuel Conditions

$$\dot{m}_\imath = \begin{cases} 0 & if\ FP = 0 \\ \dot{m}_{i,LP} & if\ FP = "low" \\ \dot{m}_{i,HP} & if\ FP = "high" \end{cases}$$

Where:

$\dot{m}_\imath$: Emissions Rate of Pollutant i

FP: Operating Firepower

LP: Low Power

The relationship between cookstove firepower and emissions rate can be demonstrated by conducting firepower sweeps. For example, CO emissions data are shown in Figure 21 for firepower sweeps with four different “rocket-elbow” style cookstoves. Details on the firepower sweep procedure (30, 31) and measurement equipment (83, 89) has been published elsewhere. The data depicted in Figure 21 support the concept of using cookstove firepower as a metric for defining emissions rates.

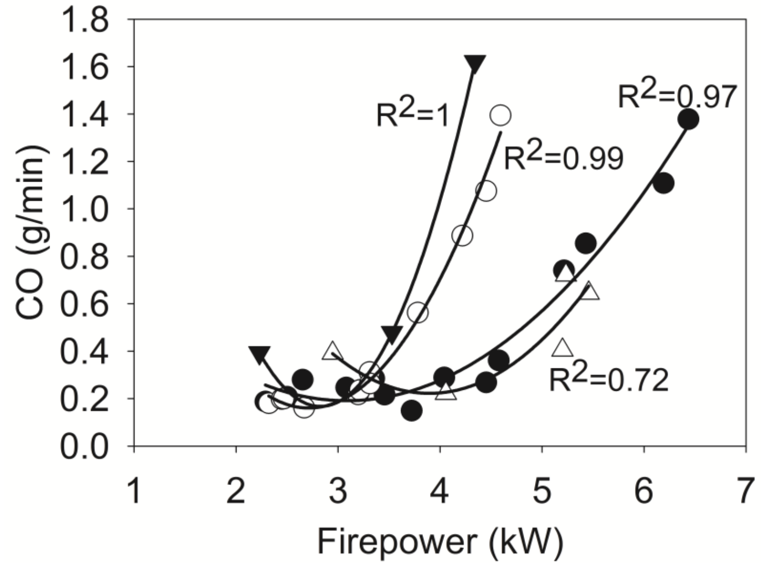

Figure 21: Demonstration of the Correlation that is Possible between Stove Firepower and Emissions Rate from Natural Draft Biomass Cookstoves

3.2.2.2. Relating Emissions Rate to Use Pattern

How a cookstove is used affects both the rate and content of the emissions released. Patterns of cookstove use vary worldwide and depend on local cooking practices and meals. Three general operating conditions were selected as inputs for the numerical model: off, low power, and high power. These simplified use patterns were chosen to simulate real cooking practices and have been defined in the Water Boiling Test (WBT) (90). The selection of only three operating conditions is a compromise between practicality and realism. In reality, cookstoves are operated over many conditions, however, models require the use of approximations and simplifications. Three operating conditions allows for different cooking practices to be evaluated while also using the WBT data that has been already collected by the cookstove sector.

Equation 2: Emissions Profile Based on Operating Condition

$$\dot{m}_i(t) = UP(t) * \dot{m}_i$$

Where:

$\dot{m}_\iota(t)$: Emissions Rate of Pollutant i at Time t

t: Time

UP: Use Pattern

3.2.2.3. Relating Emissions to Room Concentrations

Indoor pollutant concentrations resulting from biomass combustion were estimated using a single-zone mass-balance box model. This model assumes instant and perfect mixing in a geometrically indefinite space. Instantaneous and running average concentrations for carbon monoxide and particulate matter are calculated through the use of the inputs in Equation 3.

Equation 3: Mass-Balance Equation for Calculating Indoor Concentrations of Pollutants

$$\frac{d\boldsymbol{C_i}}{d\boldsymbol{t}} = \frac{\dot{\boldsymbol{m}}_{\boldsymbol{\iota}}(\boldsymbol{t}) - \boldsymbol{Q}(\boldsymbol{t}) * \boldsymbol{C_i}}{\boldsymbol{V}}$$

Where:

$\dot{m}$: Emissions Rate of Pollutant i

V: Room Volume

Q: Air Exchange Rate

C: Concentration of Pollutant i in Room

t: Time

A simple box model will not perfectly replicate real world concentrations, however, they provide sufficient accuracy for a Monte Carlo approximation (40). A common concern regarding simple box models is the assumption of a homogenous concentration, as concentration gradients always exist in a room. Although the assumption of homogenous concentrations is not perfect, this model provides a reasonable approximation of reality. Alternative methods include multi-zone models or the use of computational fluid dynamics. However, the added accuracy of these models is largely outweighed by their increased complexity. Previous studies have shown that the assumption of perfect mixing improves as the distance from the stove increases. Furtaw et al. found that when farther than 0.8m from a fire almost no difference was found between a perfect room model and experimental data (91). Spatially resolved measurements taken by Ezzati et al. found similar results for PM_{10} concentrations at a distance of 0.4m from an open fire (92). A user's proximity to a cookstove is strongly dependent on stove design and how the stove is used, however the users "breathing space" is often defined as a distance of 0.5m from a cookstove (93, 94). The assumption of perfect mixing is also aided by the long time periods associated with emissions release and exposure (95, 96, 97).

3.2.2.4. Relating Room Concentration to Dose

The health effects of pollutant exposure depend greatly on the dose received. For the case of air pollution, dose is a strong function of ambient concentration and inhalation rate. Daily dose is estimated in the model by considering ambient concentrations and daily inhalation volumes; Pope et al. (98) presented a similar approximation. An individual's inhalation rate depends on many factors, including age, sex, activity level and state of health (99). The model uses a baseline assumption of constant inhalation rate of 16m^3/day. The baseline inhalation rate was set based on studies conducted by the US Environmental Protection Agency (Figure 22) (99). Other risk assessment calculations use similar values (100, 101). Relative effects for specific sub-populations, such as children, can be investigated by changing the inhalation volumes used.

Equation 4: Time Averaged Dose Based on Average Concentration and Inhaled Volume

$$Dose = \frac{\int_{t=0}^{T} C_i(t)dt * IV}{T}$$

Where:

C_i: Concentration of Pollutant i

IV: Inhaled Volume

T: Averaging Time

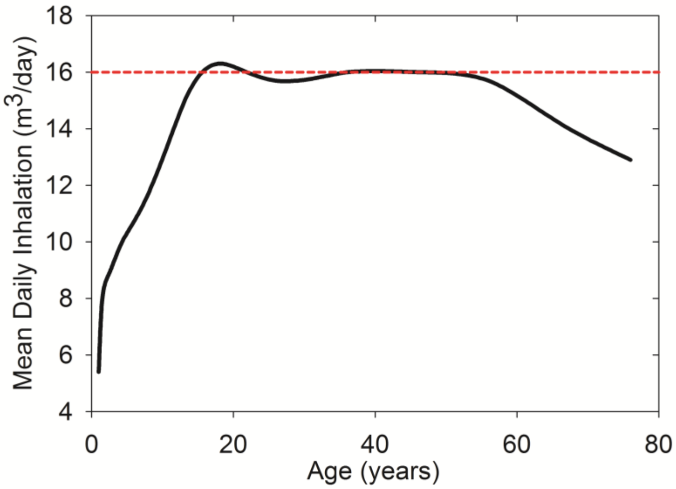

Figure 22: Estimated Mean Daily Inhalation Volume (males and females combined). Based on EPA tabular data (99)

Another simplification used in the model is that average personal exposure to a pollutant is equal to average ambient concentration. The difference between personal and ambient exposure depends on a number of factors. These factors can include concentration gradients in the room, proximity of the user to the source (in this case the cookstove), and the amount of time a person spends in a room with a running stove. Several studies have investigated the accuracy of using ambient emissions monitors to predict personal exposure (102, 103, 104, 105, 106). The studies reported mixed results. Although some studies found a good correlation between ambient concentrations of pollutants and personal exposure, this finding was not universal. Many of the studies concluded that the correlation between ambient concentrations and personal exposure depends on the situation.

A literature review was conducted to evaluate the suitability of assuming that personal and ambient air concentrations are equal in homes using biomass cookstoves (Figure 23) (107, 16, 108, 97, 109).

Although large variability existed in the data, a funnel plot analysis found no systematic bias. The current model uses the assumption that personal exposure is equal to room concentration.

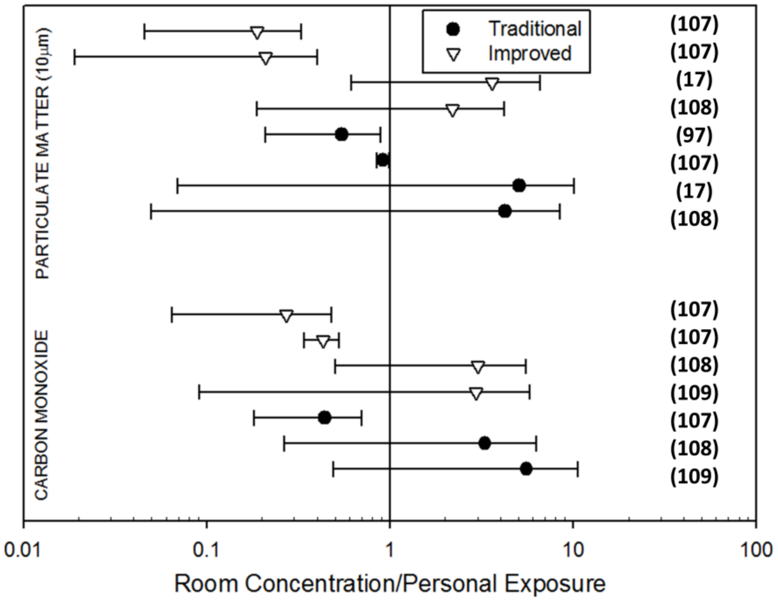

Figure 23: Ratio of Room Concentration to Personal Exposure Found in Previous Studies (107, 16, 108, 97, 109)

3.2.2.5. Relating Dose to Health Effect

Cardiovascular mortality risk is used in the model as a proxy for the overall health risk of biomass cookstove use. Particulate matter is only one of many pollutants emitted from biomass combustion that can be damaging to human health. Particulate matter was chosen for the model based on the extensive work that has gone into the health effects associated with inhalation of combustion aerosols (101, 98, 110).

Although many studies have investigated the health risks associated with high doses of combustion aerosols (e.g. smoking cigarettes) and low concentrations (e.g. secondhand smoke or ambient pollution); few studies have looked at the health effects expected from biomass cookstove use. Based on the data that is available for combustion particles, a logarithmic relationship appears evident between the inhalation of particulate matter and cardiovascular mortality risk (Figure 24). Pope et al. (98) and Smith et al. (100) discuss the dose response curve for particulate matter in more detail.

Equation 5: Estimation of Relative Risk of Cardiovascular Mortality

$$Risk = R_o + r * \log(Dose)$$

Where:

R_o: Dose Response Curve Intercept

r: Slope of Dose Response Curve

Dose: 24-Hour Dose

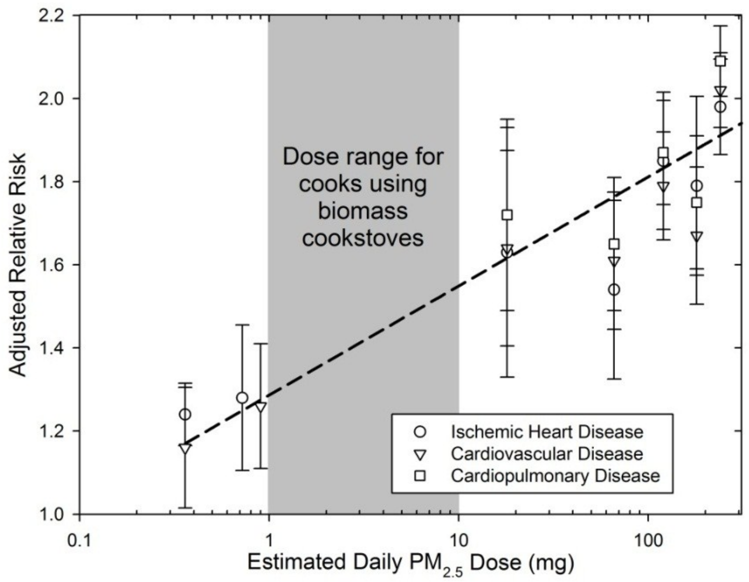

Figure 24: Adjusted Relative Risk of Cardiovascular Mortality vs. Estimated Inhaled Daily Dose of $PM_{2.5}$. Error bar represents 95% confidence interval for the individual studies used in the meta analysis conducted by Pope et al. Dotted line is the assumed dose/response line. Plot generated from tabular data presented by Pope et al. (98)

3.2.2.6. Relating Emissions to Climate Forcing

Many biomass cookstove programs seek to reduce the climate impacts of stove use. The climate impacts of a combustion device can be quantified in multiple ways. Net equivalent carbon dioxide (eCO_2) has been used here to characterize the global climate implications of biomass cookstove use. Although many factors affect climate, including deforestation, eCO_2 can be quantified in a numerical model. The climate impact from cookstoves was calculated using Equation 6.

Equation 6: Calculation of Total Equivalent Carbon Dioxide Emitted

$$eCO_2 = \sum_i m_i * GWP_i$$

Where:

eCO_2: Total Equivalent Mass of Carbon Dioxide

m_i: Mass Emitted of Pollutant i

GWP_i: Global Warming Potential of Pollutant i

Five compounds have been used to calculate total eCO_2 emissions: carbon dioxide, carbon monoxide, methane, black carbon, and organic carbon. A 100-year time horizon was used was used to evaluate global warming potentials (GWP).

Table 6: Global Warming Potential for the Compounds Considered in the Model Based on a 100 Year Time Horizon (111, 112). Global warming potential factors are unit less multiplication factor of impact as compared to the forcing factor of carbon dioxide.

Compound	Global Warming Potential
Carbon Dioxide (CO_2)	1
Carbon Monoxide (CO)	1.9
Methane (CH_4)	25
Elemental Carbon (EC)	650
Organic Carbon (OC)	-75

The climate impacts of biomass combustion depend on factors beyond emissions. For example, how fuel is gathered may also produce climate-relevant effects. Fuel from sustainable sources, such as from "fuel farms" or by biomass that is produced as waste from another process, changes the net carbon emitted to the atmosphere. The model includes an option for defining the estimated renewable fuel fraction used.

Equation 7: Calculation of Carbon Reduction that can be Claimed

$$C\_eCO_2 = (T\_eCO_2 - I\_eCO_2) * fNRB$$

Where:

C_eCO_2: Total eCO_2 that can be Claimed as a Reduction

T: Traditional Cookstove

I: Improved Cookstove

fNRB: Fraction Non-Renewable Biomass Fuel

3.3. Model Evaluation

Simulation results are only as valuable as the inputs used. One advantage of probabilistic modeling is that the models can use relatively imprecise input data as long as these data are accurate. Data accuracy ensures that the simulations produce distributions with the correct magnitude. Low precision, but accurate, data only changes the interpretation of results. Low precision data results in wide distributions indicating the need for more information. However, there is no universal standard regarding acceptable precision for Monte Carlo simulation. The feasibility of using the model to generate informative data was evaluated by comparing model simulations to experimental results.

For a model to be useful, the gathering of the inputs must be practical. Simulations were run using easily collected data to evaluating model feasibility. Two components were considered when evaluating model feasibility: (a) could the model predict pollutant concentrations in a home, and (b) could the model produce realistic performance distributions. Achieving both of these would be required for the model to provide useful information to the cookstove sector.

3.3.1. Model Evaluation: Simulating Indoor Air Quality

The model's ability to generate realistic predictions of pollutant concentrations in a home was tested by comparing simulation results to experimental data taken by the author in the Southern Nations, Nationalities and Peoples region of Ethiopia. For this study, carbon monoxide monitors were placed in a home where injera bread was baked on a traditional three-stone fire. Detailed notes were taken throughout the cooking process to catalog the use pattern of the stove. The cookstove was considered to be either off, operating at a low power, or at a high power, based on visual observation. A simulated emissions profile was generated from these data (Figure 25).

A reasonable approximation for indoor pollutant concentrations was achieved using the model. The strength of the model was evaluated using the American Society of Testing and Materials (ASTM) room air model criteria (113). The model passed all criteria with the exception of the correlation coefficient (r) (Table 7). The model did not achieve the target criterion for the Pearson correlation coefficient because of the coarse temporal nature of the inputs. The model inputs used for use pattern did not include the small fluctuations in firepower that occur when wood is added the cookstove. Despite the temporal limitation of the inputs, the model provided a sufficiently accurate prediction. The model captured the relative magnitude and pattern of harmful pollutant emissions.

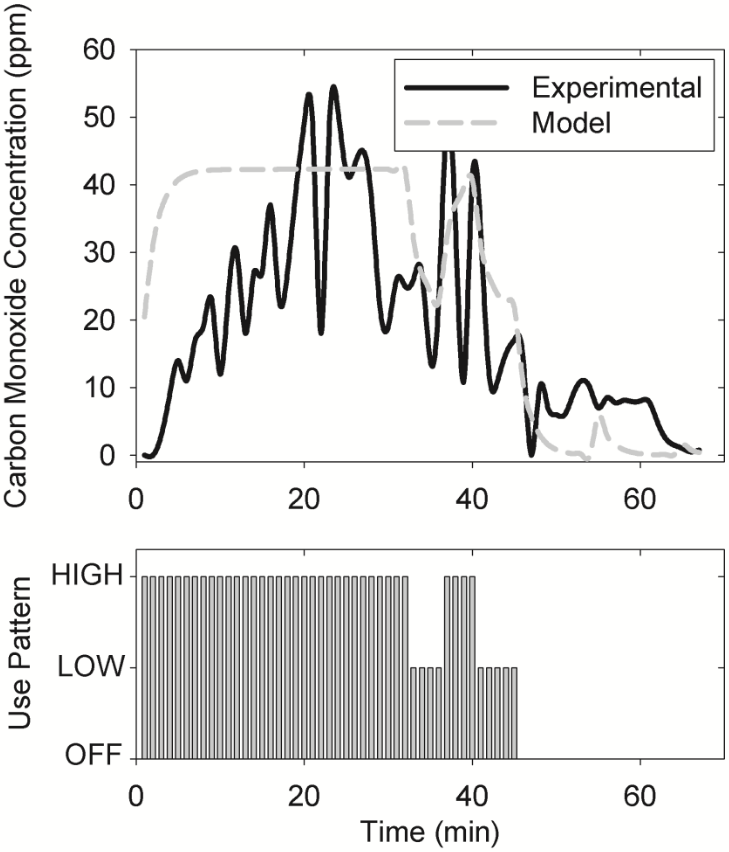

Figure 25: Experimental and Modeled Air Concentration in a Home Using a Traditional Three-Stone Fire

Table 7: Evaluation of Room Concentration Model Against ASTM D5157 Standard

ASTM Criteria	Pass/Fail
r≥0.9	Fail
0.75<slope<1.25	Pass
NMSE≤0.25	Pass
FB≤0.25	Pass
FS≤0.5	Pass

3.3.2. Model Evaluation: Estimating Cookstove Performance Data

The ability of the model to generate realistic distributions of cookstove performance data was evaluated by simulating the pollution distributions measured by Ezzati et al. in Kenya (94). Performance distributions generated by the model for carbon monoxide were compared to experimental data for both a traditional three-stone fire (wood stove) and a ceramic Jiko (charcoal stove). Model inputs were derived from multiple sources (Table 8) with several simplifying assumptions. Many of the assumptions made were required due to the limited data available. For example, Ezzati et al. only defined periods of "burning," no details were available about how the stove was operated (i.e. high power, low power, total fuel used, etc.). Therefore, stoves were assumed to operate at a constant firepower. A second assumption was that the stoves ran long enough that the room achieved a steady state concentration and that this steady state concentration was achieved quickly; therefore, the average concentration of the room could be assumed equal to the steady state concentration. Simulated distributions were generated for each cookstove based on 10,000 model iterations.

Table 8: Parameters Used to Evaluate Ability of Model to Predict Realistic Distributions of Performance. All parameters were assumed to have a normal distribution.

Parameter	Mean Value	Standard Deviation	Source Used to Estimate Values
Three-Stone Fire: Carbon Monoxide Emissions Factor (mg/min)	1045	65	(80)
Ceramic Jiko: Carbon Monoxide Emissions Factor (mg/min)	1780	183	(80)
Home Size (m^3)	20	2	(23, 114)
Air Exchange Rate (1/hr)	40	20	(21, 114)

The model agreed relatively well with experiment data for both cookstoves evaluated (Figure 24). Modeled and measured room concentration distributions did cross zero, however, due to the assumption of normality – a limitation of the data reported by Ezzati el al. Box plots generated by Ezzati et al. indicate that measured concentration distributions were non-normal and right skewed. However, lacking sufficient information to define these distributions further, a normal distribution was used for both the model and for re-plotting the original study data (94). The results are encouraging; the model was able to predict performance distributions similar to the experimental study without knowing specific details of stove use, design, or fuel conditions.

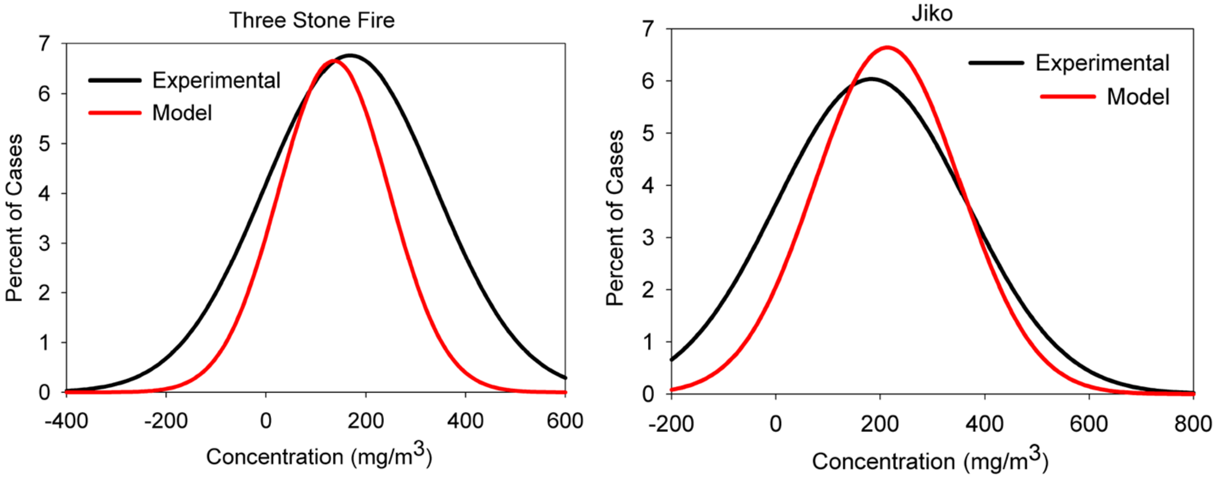

Figure 26: Comparison of Experimental and Predicted Performance Distributions of Indoor Carbon Monoxide Concentrations for a Three Stone Fire and Charcoal Jiko Cookstoves

3.3.3. Sensitivity Study

Model sensitivity is as important as model accuracy. A sensitive model requires highly precise inputs to produce accurate results, which reduces the practicality of the model. Sensitivity was evaluated for two categories, informational sensitivity and model sensitivity. Informational and model sensitivity have different implications and are addressed in different manners. Model sensitivity is when a change is needed in the actual model code, for example the global warming potential of different pollutants. Informational sensitivity represents components that would be improved by changing model inputs, for example, the assumed emissions rate of a cookstove. Model sensitivity points to a weaknesses in the actual model where informational sensitivity implies a need for more accuracy input data.

A sensitivity study was conducted to investigate how key model parameters influenced simulation results. Model sensitive was broken into two categories, information sensitivity (IS) and design sensitivity (DS). Parameters were classified as contributing to either IS or DS (or both) based on what steps would be taken to reduce the impact of that parameter on overall result variability. A model parameter was considered to affect information sensitivity if simulation variability could be reduced by using more precise data. For example, there could be sensitivity to the room volume used, which would imply detailed information is needed on where cookstove designs are being used. A model parameter was considered to affect design sensitivity if it could only be addressed by revising how calculations were conducted, for example the inhalation rate that is used in the model. Although general guidelines were used to classify components as affecting IS or DS, classifications were subjective. Sensitivity was quantified by comparing a baseline case to model results when each parameter was changed independently.

Table 9: Sensitivity Study Model Parameters and Resulting Simulation Variation. IS designates informational sensitivity and DS design sensitivity. Sensitivity to changes in model parameters is represented as a percentage change from the baseline case

PARAMETER	IS?	DS?	BASELINE VALUE	VARIATION	CHANGE IN MORTALITY RISK	CHANGE IN eCO_2	CHANGE IN FUEL COST
Room Volume	**YES**	**YES**	$40m^3$	$+5\ m^3$	-0.8%	Independent	Independent
Air Exchange Rate	**YES**	**YES**	15/hour	+3 exchanges/hour	-1.1%	Independent	Independent
Inhalation Rate	**YES**	**YES**	$16\ m^3$/day	$+1\ m^3$/day	+0.4%	Independent	Independent
Mortality Regression Slope	No	**YES**	0.0978 Risk/mg	+0.015 Risk/mg	+1.9%	Independent	Independent
Mortality Regression Intercept	No	**YES**	1.33 Risk	+0.2 Risk	+13.1%	Independent	Independent
Global Warming Potential	No	**YES**	Table 6	+10%	Independent	10%	Independent
Fuel Cost	**YES**	no	$15/tonne	+$1/tonne	Independent	Independent	6.6%
Use Pattern	**YES**	**YES**	3 hours at high power	+1 hour	+1.8%	33.3%	33.3%
Emissions Rate	**YES**	**YES**	Table 10	+10%	+0.6%	10%	Independent
Fuel Rate	**YES**	**YES**	Table 10	+10%	Independent	Independent	10%

Table 10: Emissions and Fuel Use Rates Used to Evaluate Model Sensitivity. Rates are only meant to serve as approximations of real stove performance for the purposes of evaluating the model. Data used was from Jetter et al. (80) and the authors

	High Power Emissions Rate
CO Rate (g/min)*	0.90
CO_2 Rate (g/min)*	45.0
CH_4 Rate (g/min)*	3.5E-02
$PM_{2.5}$ Rate (g/min)*	7.5E-02
Black Carbon (g/min)**	8.0E-03
Organic Carbon (g/min)**	2.5E-02
Fuel Rate (g/min)*	25
	**Jetter et al. data* ***Author data*

Model sensitivity to different parameters was characterized by taking the ratio of output (i.e., model results) to input change (Figure 27). A ratio of zero indicates that the output metric is independent of a change to model input whereas a ratio of one indicates a direct, one-to-one relationship between results and the input. Fuel cost and eCO_2 were more sensitive to model inputs than mortality risk; fuel cost and eCO_2 are directly proportional to the inputs whereas health effects are not. Although there are many opportunities for improving the components of the model, immediate gains can be realized from more accurate data on cookstoves use (e.g., fuel rate and use pattern) and emissions (e.g., pollutant emissions rates and global warming potential of those emissions).

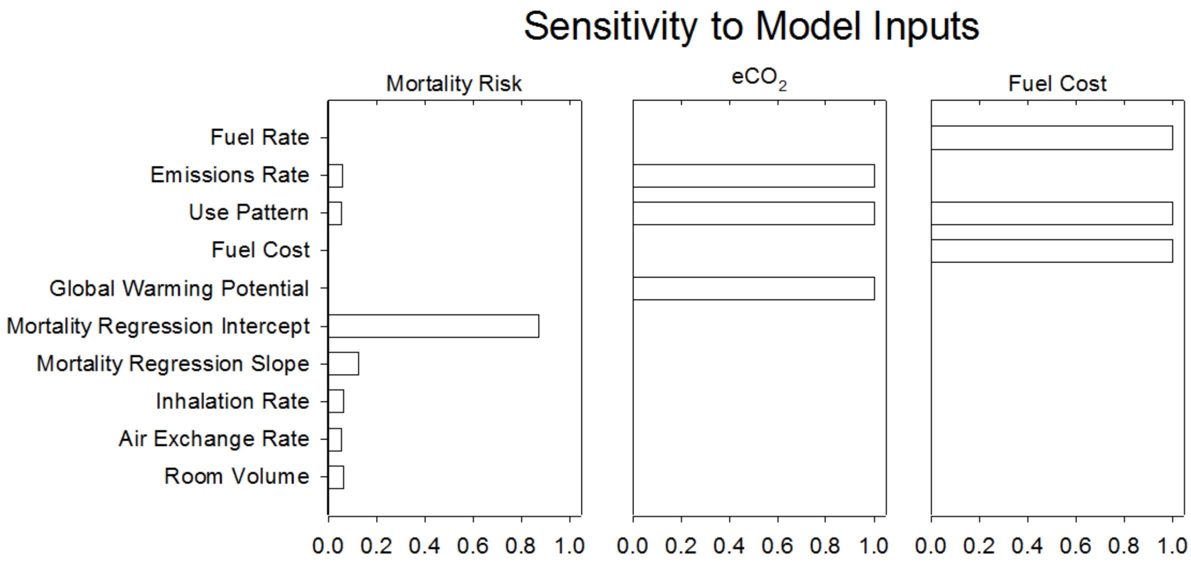

Figure 27: Ratio of the Change in Metric of Performance to Corresponding Change in Model Input

3.4. Future Applications and Development of Numeric Cookstove Models

The modeling framework presented here has the potential to provide invaluable data to the cookstove sector. Numerical models can help stove designers and developers evaluate the potential of a design prior to field deployment and testing. Probabilistic models can also provide program developers with a decision-making tool prior to selecting a cookstove design. During the process of developing the model the authors have identified a number of topics that warrant future research and development efforts.

1. Room Concentration Prediction: Evaluation of the indoor air quality model showed two periods of stove operation that need to be investigated in greater detail: the period in which the stove is first starting up and the smoldering period after that stove has been put out but before emissions have stopped. The original use pattern assumed that the stove immediately came to full high power, which is not the case. The use pattern also did not account for smoldering.

2. Cooking Cycles: The model currently defines the use pattern based on cookstove fire power. Results that are more informative could be achieved by incorporating a heat transfer component. A task based cooking cycle would allow the model to target cooking cycles (i.e. cooking pot temperature) instead of operating firepowers.

3. Laboratory/Field Connection: A better understanding of what makes a cookstove perform differently in the field compared to the laboratory is needed. It is anticipated that elements such as fuel moisture content, fuel size, etc. would all be beneficial to increasing the accuracy of the predictions generated by the model.

4. A Computational Tool for Quantifying and Monetizing Biomass Cookstove Impact[5]

4.1. Introduction

Improving the performance of biomass cookstoves could enrich billions of lives as well help mitigate global climate change. Countless cookstove programs around the world are working to promote the use of improved cookstoves and for many programs, the number of cookstoves disseminated will depend on available capital. Because projects are often capital limited, making informed programmatic decisions requires understanding the cost/benefit relationships associated with different intervention options. Programmatic decisions regarding cookstove selection are often based on maximizing either the health or the climate improvements that can be achieved within the project budget.

Comparing different cookstove options presents a number of challenges, one of which is quantifying performance. Performance can be measured in many ways; it is quantified in the model as the amount of pollutants emitted. Many factors affect cookstove performance, and correspondingly, these factors also influence the potential benefits associated with using a particular design. Two factors that have major influence on cookstove performance are how and where a cookstove is used. These two factors are only partially related to the design of the cookstove itself, yet predicting the performance of a cookstove in the field requires consideration of these situational variables.

A numeric model has been developed for quantifying and monetizing biomass cookstove performance. The tool considers how and where cookstoves are used to calculate location specific cost/benefit relationships for different cookstove designs. Theoretical intervention programs were simulated to demonstrate the tool and methodology. Four use patterns at two locations for four

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[5] The work presented in this chapter is based on the publication currently in preparation: L'Orange, C., DeFoort, M. A Computational Tool for Quantifying and Monetizing Biomass Cookstove Impact.

cookstove designs were simulated to illustrate the importance of considering location and cooking habits when evaluating the performance of biomass cookstoves.

4.1.1. Health Implications of Biomass Cookstove Use

The combustion of biomass fuels in traditional cookstoves can result in the release of toxic levels of harmful pollutants. Indoor exposure to these pollutants contributes to an estimated 2 million deaths annually from acute lower respiratory diseases (5). To date, many health problems have been associated with exposure to the pollutants released from biomass cookstoves. These adverse effects include damage to the respiratory, cardiovascular, and nervous systems. Studies funded by the World Health Organization (WHO) have indicated that the inhalation of smoke from biomass combustion doubles the risk of respiratory diseases in children (7, 9).

4.1.2. Climate Implications of Biomass Cookstove Use

Biomass cookstoves affect local and global climate. Although biomass fuels have the potential to supply near carbon-neutral energy, many cookstove designs are inefficient. Cookstove efficiency is often quantified in two ways, combustion efficiency and thermal efficiency. Combustion efficiency is defined as the ratio of carbon emitted in any form besides carbon dioxide to total carbon. Thermal efficiency is the ratio of energy that went into cooking to the total energy that was in the fuel. Details on calculating combustion and thermal efficiencies can be found in the Water Boiling Test protocol (90). The climate impacts of cookstoves depend on how the fuel is gathered and the levels of pollutants emitted during use (4, 12). Whereas improvements to the thermal efficiency of cookstoves would reduce the total carbon emitted into the atmosphere, improvements to the combustion efficiency of stoves would produce emissions with lower global warming potentials (GWP). Experts predict that improving combustion efficiency could the global warming effect of cookstoves in half (12).

4.2. The Use of a Numeric Model to Evaluate Cookstove Performance

A numeric method for predicting the impact of biomass cookstoves has been developed. The model considers geographical location, cooking habits, and various stove performance metrics. The model evaluates cookstove impact by estimating reductions in cardiovascular mortality risk and equivalent carbon dioxide (eCO_2) associated with the use a given cookstove design and as compared to the use of a traditional three stone fire. The model then monetizes these two forms of impact using best-available economic data. These metrics of impact are calculated using the framework presented in Figure 28.

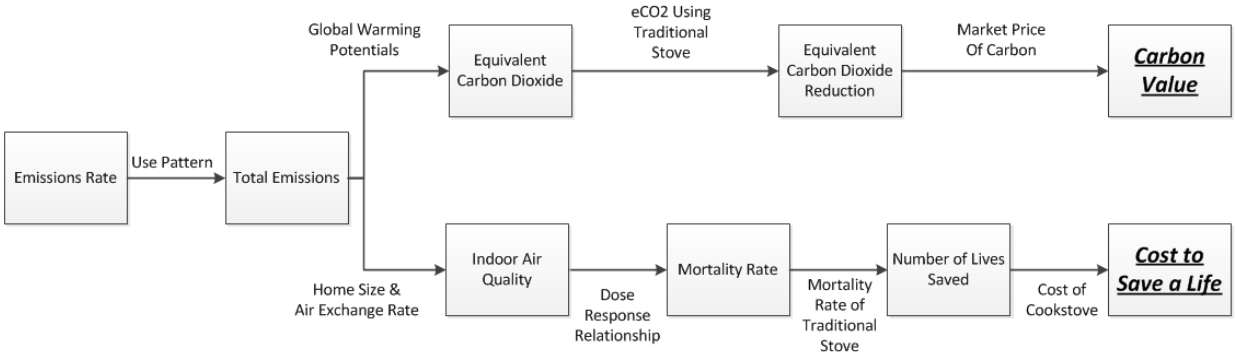

Figure 28: Cookstove Impact Prediction Model

The model considered the impacts of four cookstove designs: a traditional three-stone fire, a ceramic upesi, a G3300 “rocket-elbow” design by Envirofit International, and top-lit updraft gasifier designed by Philips. These cookstove were selected as they cover a range of possible “improved” technologies. The upesi is an artisan-produced cookstove that can be made at very low cost but my not always be a substantial improvement over traditional designs. The Envirofit International G3300 is a mass produced design that seeks to balance cost and performance. Gasifier cookstoves have the potential to have ultra-clean performance but are often very expensive. Four cooking processes and two different home sizes were simulated (eight scenarios per cookstove). These situational variables were selected to demonstrate the importance of context when evaluating the impact of a biomass cookstove. For each combination of cookstove by scenario, the average emissions rate as well as one standard deviation above and below the average emissions rate were simulated (Table 11). Following these simulations, a sensitivity study was conducted to evaluate the robustness of the model's findings. Model input data are described in detail below.

Table 11: Testing Matrix

	Scenario #1	**Scenario #2**	**Scenario #3**	**Scenario #4**
Kitchen #1	Three Stone Fire (3x) Upesi (3x) G3300 (3x) Philips (3x) ***12 Runs***	Three Stone Fire (3x) Upesi (3x) G3300 (3x) Philips (3x) ***12 Runs***	Three Stone Fire (3x) Upesi (3x) G3300 (3x) Philips (3x) ***12 Runs***	Three Stone Fire (3x) Upesi (3x) G3300 (3x) Philips (3x) ***12 Runs***
Kitchen #2	Three Stone Fire (3x) Upesi (3x) G3300 (3x) Philips (3x) ***12 Runs***	Three Stone Fire (3x) Upesi (3x) G3300 (3x) Philips (3x) ***12 Runs***	Three Stone Fire (3x) Upesi (3x) G3300 (3x) Philips (3x) ***12 Runs***	Three Stone Fire (3x) Upesi (3x) G3300 (3x) Philips (3x) ***12 Runs***

96 Simulation Runs

Sensitivity Study	**Variation**
#1	Scenario #1, Theoretical Room #1, Upesi, Baseline Emissions: Vary room size +15% ***(1 run)***
#2	Scenario #1, Theoretical Room #1, Upesi, Baseline Emissions: Vary air exchange +15% ***(1 run)***
#3	Scenario #1, Theoretical Room #1, Upesi, Baseline Emissions: Vary Price +15% ***(1 run)***
#4	Scenario #1, Theoretical Room #1, Upesi, Baseline Emissions: Vary Life +1 Year ***(1 run)***
#5	Scenario #1, Theoretical Room #1, Upesi, Baseline Emissions: Vary inhalation rate +15% ***(1 run)***

5 Sensitivity Runs

101 Total Runs

4.2.1. Establishing Model Inputs for Theoretical Cookstove Programs

4.2.1.1. Defining Cookstove Performance

Cookstove emissions rates depend on stove design, fuel type and condition, and how a stove is being operated (30, 31, 32). The model assumes that a cookstove is either off, operating at low power, or operating at high power. High power operation, as defined here, is the average of the cold start and hot start phases of the Water Boiling Test (90) with the simmer phase used as low power.

The selected cookstoves include a range of technologies for which reliable emissions data are available. Gaseous emissions data for the stoves came from studies conducted by the US Environmental

Protection Agency (80). Aerosol emission data came from the Engines and Energy Conversion Laboratory (EECL) at Colorado State University. Particles were sampled isokineticly from an emissions hood on quartz and polytetrafluoroethylene (PTFE) filters. Elemental (EC) and organic carbon (OC) were quantified with a Sunset Laboratories OC-EC Aerosol Analyzer using NIOSH method 5040. A microbalance (Mettler Toledo MX5) was used to measure PM mass collected by PTFE filters; this balance has an accuracy and resolution of ±1μg. A description of the experiment set-up and associated measurement techniques is available elsewhere (83).

Water Boiling Tests (WBT) (90) were conducted using the three-stone fire, G3300, and Philips gasifier to collect aerosol data. The Upesi stove was not available at the EECL during testing to collect aerosol emissions data. To fill in the missing data, the aerosol ratio between the G3300 and the Upesi was taken to be the same as the gas phase ratio for the stoves resulting in the high power rate of the Upesi being 40% greater than the G3300, and the low power rate 75% higher.

Table 12: High Power and Low Power Performance Data for Four Biomass Cookstoves (80). Emissions data represent average values ± one standard deviation.

High Power

	PM$_{2.5}$ Rate (g/min)^2	CO Rate (g/min)^1	CO$_2$ Rate (g/min)^1	CH$_4$ Rate (g/min)^1	Black Carbon (g/min)^2	Organic Carbon (g/min)^2
Three Stone Fire	3.0 E-2 ± 3.3 E-3	0.9 ± 0.1	43 ± 3	3.5 E-2 ± 6.8 E-3	7.9 E-3 ± 1.2 E-3	2.2 E-2 ± 5.4 E-3
Upesi^3	2.3 E-2 ± 2.3 E-3	0.8 ± 0.1	32 ± 1	5.1 E-2 ± 9.8 E-3	1.4 E-2 ± 1.4 E-3	9.0 E-3 ± 9.0 E-4
Envirofit G3300	1.6 E-2 ± 1.6 E-3	0.6 ± 0.2	26 ± 3	3.3 E-2 ± 1.1 E-2	9.7 E-3 ± 2.7 E-3	6.4 E-3 ± 5.4 E-4
Philips Gasifier	4.4 E-3 ± 9.4 E-4	0.1 ± 0.1	28 ± 2	2.2 E-3 ± 2.0 E-3	4.5 E-4 ± 2.3 E-4	3.9 E-3 ± 1.7 E-3

Low Power

	PM$_{2.5}$ Rate (g/min)^2	CO Rate (g/min)^1	CO$_2$ Rate (g/min)^1	CH$_4$ Rate (g/min)^1	Black Carbon (g/min)^2	Organic Carbon (g/min)^2
Three Stone Fire	2.9 E-2 ± 3.3 E-3	1.0 ± 0.1	28 ± 2	3.2 E-2 ± 6.2 E-3	7.5 E-3 ± 6.5 E-4	2.2 E-2 ± 5.9 E-3
Upesi^3	1.6 E-2 ± 1.6 E-3	0.6 ± 0.1	24 ± 1	2.4 E-2 ± 1.1 E-3	4.9 E-3 ± 4.9 E-4	1.1 E-2 ± 1.1 E-3
Envirofit G3300	9.0 E-3 ± 5.3 E-4	0.3 ± 0.1	13 ± 0.4	3.7 E-3 ± 2.1 E-3	2.8 E-3 ± 4.4 E-4	6.2 E-3 ± 6.2 E-4
Philips Gasifier	5.5 E-3 ± 8.0 E-4	0.1 ± 0.0	12 ± 1	2.0 E-3 ± 1.4 E-3	7.8 E-4 ± 1.7 E-4	4.8 E-3 ± 1.4 E-3

(1): Gaseous data taken by the EPA
(2): Aerosol data collected by the EECL
(3): Aerosol Upesi data estimated. High power assumed to be 140% of G3300. Low power assumed to be 175% of G3300. An uncertainty of 10% was used for Upesi PM data.

4.2.1.2. Defining Cookstove User Patterns

Cooking patterns in the real world vary greatly. Four theoretical cooking practices were simulated. In scenario 1 the cookstove was only operated for a short period, this might occur if the stove was only used to prepare coffee, tea or a simple breakfast. Scenario 2 simulated a pattern where multiple meals were cooked each day and the stove was operated at both high power and low power conditions. Scenario 3 simulated regions of the world where the food being prepared requires long periods of simmering at low temperatures, such as when preparing beans or legumes. The fourth scenario simulated a period of extended high power operation, which is common in commercial situations such as restaurants and hotels.

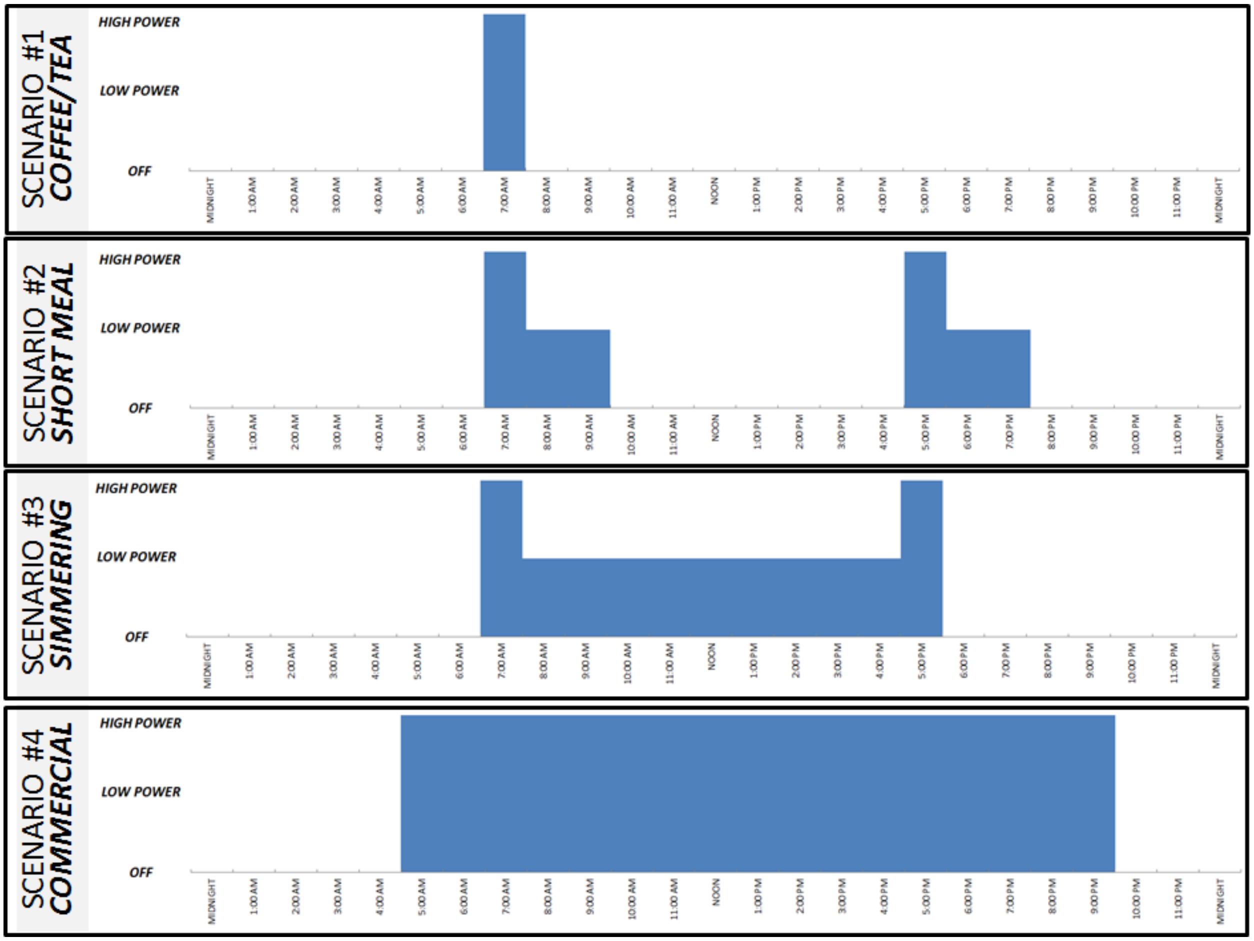

Figure 29: Simulated Cooking Patterns

4.2.1.3. Establishing a Database of Typical Kitchen Sizes and Air Exchange Rates

Indoor air quality is dependent on both room size and room ventilation. Room sizes and air exchange rates of homes using biomass cookstoves was determined through a literature review. The literature review included data from 12 countries (16, 17; 18; 19; 20; 21; 22; 23; 24; 25) (26; 27; 28; 29).

Two theoretical rooms were simulated to account for different home sizes found around the world (Table 13). The first room was small and tightly sealed as might be seen in regions that experience cool weather such as Tibet (26). The second theoretical home was larger with a higher air exchange rate. Similar homes are found in warm, dry climates such as India (21). The theoretical homes represent two realistic, but different, conditions in which biomass cookstoves are used.

Table 13: Room Volume and Air Exchange Rate for Two Theoretical Rooms

	Room Volume (m^3)	Air Exchange Rate (1/hr)
Theoretical Room #1	22	5
Theoretical Room #2	38	28

4.2.1.4. Defining Cookstove Price and Projected Life

Cost and durability estimates were determined through a second literature review (Table 14). The longevity of a cookstove depends on how and how often the cookstove is used. The model assumes the life of each stove design is a constant regardless of use pattern as little published data is currently available on the operational lifespan of biomass cookstoves (115, 116, 117). Groups such as the Global Alliance for Clean Cookstoves are working to increase understanding of this issue (118), and as knowledge in the sector improves, more refined input data can be used. Model sensitivity to this assumption is explored further in sensitivity analyses below.

To account for different anticipated lives for cookstoves, an equivalent annual purchase price (EAPP) has been used to represent cookstove cost. The EAPP is the cookstove price divided by its estimated life.

For example, a \$5.00 stove with a 5-year life would have an equivalent annual purchase price of \$1.00/year. Secondary capital costs or benefits (such as repair costs or fuel savings) were not included as part of the current analysis.

Table 14: Estimated Cost and Life for Three Biomass Cookstoves

STOVE DESIGN	TOTAL ESTIMATED COST (Source)	ESTIMATED LIFE	EAPP
Upesi	\$5.00 (115, 94)	1 Years	\$5.00/year
Envirofit G3300	\$30.00 (116, 119, 120)	3 Years	\$10.00/year
Philips Gasifier	\$120.00 (117)	5 Years	\$24.00/year

4.2.3. Numerical Models to Predict Cookstove Performance

4.2.3.1. Estimating Climate Impacts Based on Cookstove Performance

Climate-related effects have been monetized by evaluating the potential for each cookstove to produce carbon credits. The price of carbon necessary to make each cookstove cost-neutral was determined for each scenario. The higher the eCO_2 reduction (and corresponding positive climate impact), the lower the carbon price required for the program. Although the reduction in eCO_2 from using an improved cookstove could be directly monetized, carbon prices present an additional point of comparison. Using carbon prices not only allows a comparison of cookstove designs, but also gives an indication of carbon program practicality. A low carbon price indicates a higher likelihood that a program could be sustainably financed using carbon credits. Climate impacts from cookstoves were calculated using Equation 8 (121, 122). These case studies assumed a worst-case scenario of 100% non-renewable fuel. Evaluation of renewably harvested fuels will be the subject of future work.

Equation 8: Calculation of Total Equivalent Carbon Dioxide Emitted

$$eCO_2 = \sum_i m_i * GWP_i$$

Where

eCO_2: Total equivalent mass of carbon dioxide

m_i: Mass emitted of pollutant i

GWP_i: Global warming potential of pollutant i

Five pollutants were used to calculate eCO_2 emissions, including: carbon dioxide (GWP=1), carbon monoxide (GWP=1.9), methane (GWP=25), black carbon (GWP=650) and organic carbon (GWP=-75) (111, 112). Global warming potentials (GWP) for were evaluated on a 100-year time horizon.

4.2.3.2. Estimating Health Impacts Based on Cookstove Performance

Cardiovascular mortality risk has been used as a proxy for the health risks associated with biomass cookstove use. Although the health concerns associated with biomass cookstoves extend well beyond particulate matter, PM was selected as the dose/response is reasonably well established and it is a pollutant that is often measured. Pope et al. (98) and Smith et al. (100) have discussed the log-linear relationship between PM dose and cardiovascular mortality risk (Figure 30).

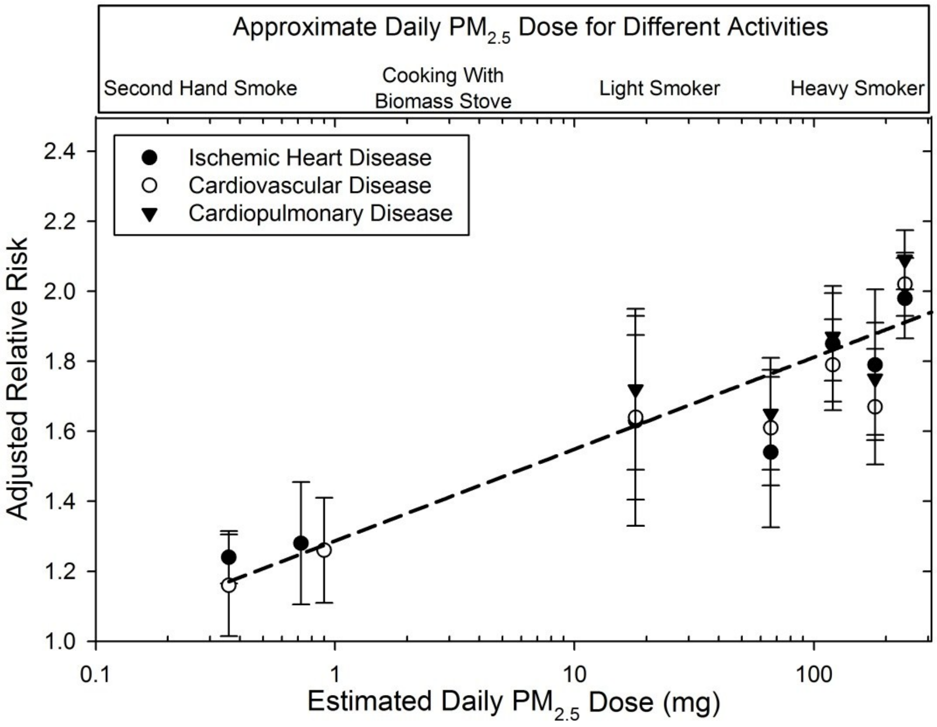

Figure 30: Adjusted Relative Risk of Cardiovascular Mortality vs. Estimated Daily Dose of $PM_{2.5}$. 95% confidence intervals represented by error bars.

The health impacts of different cookstove designs were evaluated in terms of the monetary cost associated with averting one death (Equation 9). A baseline cardiovascular mortality rate of 195.2 deaths per standard population of 100,000 was used (123). As the adjusted risk increases, the deaths attributable to cardiovascular conditions also increase. The difference in anticipated cardiovascular deaths between the traditional three-stone fire and an improved cookstove design gives an estimate of averted deaths. Normalizing the cookstove investment cost (EAPP) by the number of averted deaths gives an estimated investment cost to save one life.

Equation 9: Investment Required to Save One Life

$$I_L = \frac{EAPP}{m_B * (R_T - R_I)}$$

Where

m_B: Cardiovascular mortality rate baseline

EAPP: Equivalent Annual Purchase Price

R_T: Mortality risk associated with traditional stove

R_I: Mortality risk associated with improved stove

I_L: Investment required to save one life

Simulating Air Pollutant Concentrations in a Room

A mass-balance air quality model was used to estimate indoor air concentrations. The model assumes instant and perfect mixing of pollutants. Although rooms are never perfectly homogenous, indoor concentrations estimated using such models correlate well with experimental data in homes (40). Equation 10 was used to calculate carbon monoxide and particulate matter concentrations. During development, model accuracy was validated by comparing results to the IAQX model developed by the Environmental Protection Agency (124).

Equation 10: Generic Indoor Air Quality Model Formulation

$$\frac{dC}{dt} = \frac{\dot{m}(t) - Q(t) * C}{V}$$

Where

C: Concentration of pollutant in room

$\dot{m}$: Emissions rate of pollutant

Q: Air exchange rate in room

V: Volume of room

For women cooking with biomass cookstoves, the bulk of their exposure occurs at home. Ezzati et al. found that as much as 75% of a women's exposure came from their time within the home (125). The high fraction of in-home exposure can be attributed to the corresponding time spent near the cookstove. Women often spend multiple hours a day within a few meters of a burning cookstove (10).

Dose vs. Exposure

Inhaled dose depends on numerous factors including concentration, intake volume rate, exposure duration, size distribution (in the case of PM), and deposition fraction. Although these values do fluctuate with activity, a constant inhalation rate of $16m^3$/day was used (100, 99, 101). Daily dose was estimated from the total daily air intake and a 24 hour average concentration. Pope et al. (98) utilized a similar assumption.

4.3. Results

Cookstove impact has been put into context by presenting the results in comparison to a traditional three-stone fire. Results have been presented as average and upper bound/lower bound estimates. For the simulations presented here, cookstove emissions rates are the only input data with uncertainty. However, model sensitivity to other inputs is also explored in subsequent sections.

4.3.1. Determining the Ideal Cookstove for a Program

What makes a particular cookstove "optimum" for a program depends on factors beyond just design and performance. Factors such as how and where a stove is used affect whether a design is appropriate for a particular program, and monetary considerations will influence whether the investment is justified. Many times decisions are based on cost/benefit tradeoffs. What design will have the shortest payback period? What design will have the greatest impact per dollar invested?

Carbon credits receive a lot of attention in the cookstove sector as a possible mechanism to offset the costs of cookstove programs (126, 127, 128). The carbon credit process can be time-consuming; many programs may need to begin the application process prior to conducting extensive field testing. Without an early and reliable indicator of programmatic performance/success, cookstove programs operate under great risk regarding economic viability. Table 15 demonstrates how use patterns and stove performance metrics interact to drive cost neutrality (from the standpoint of carbon costs) when a cookstove program is reliant on carbon credits. The carbon price that would be needed for a cookstove to be cost-neutral varied by more than 20X for some of the scenarios considered.

Table 15: Cost of Carbon Required for Program to, on Average, Break Even on Cookstove Costs (USD/tonne eCO_2) with Prediction Bounds. AVEARGE (LOWER BOUND; UPPER BOUND) **An N/A indicates that more eCO_2 was emitted than the baseline case, therefore the cookstove would not be eligible for carbon credits. All prices are based on the value of one tonne of equivalent carbon dioxide.**

			Upesi	Envirofit G3300	Philips Gasifier
SCENARIO	1	COFFEE/TEA	**$38.10** ($18.20; N/A)	**$28.40** ($18.00; $67.30)	**$52.60** ($40.70; $74.60)
	2	SHORT MEAL	**$6.90** ($3.70; $47.60)	**$4.40** ($3.40; $6.20)	**$8.60** ($7.20; $10.60)
	3	SIMMERING	**$3.80** ($2.20; $18.60)	**$2.40** ($1.90; $3.10)	**$4.70** ($4.00; $5.60)
	4	COMMERCIAL	**$2.30** ($1.10; N/A)	**$1.70** ($1.10; $4.00)	**$3.10** ($2.40; $4.40)

The cleanest stove may not necessarily be the best stove for a carbon program. Although the Philips gasifier has the potential of drastically reducing eCO_2, the high purchase price of the stove would also require the high carbon prices to be cost-neutral. Recent years have seen a dramatic change in the price of carbon (Figure 31). Cookstoves that once may have been good options for a carbon program may not be feasible in today's market.

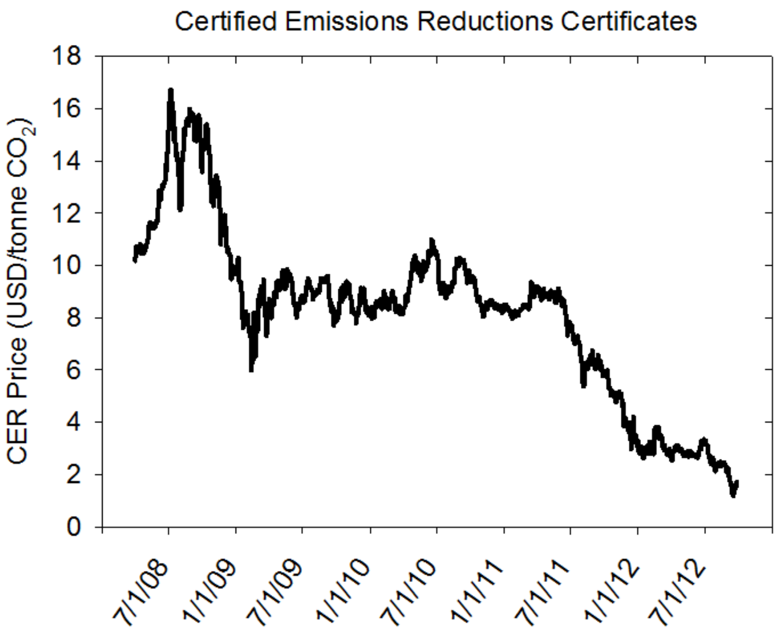

Figure 31: Market Price for Certified Emissions Reduction Certificates from April 2008 to September 2012 (129). Certified Emissions Reductions (CER) are issued through the Clean Development Mechanism

The cost effectiveness of cookstove design options has been expressed in terms of the investment required to prevent one death due to cardiovascular diseases (Table 16). The cardiovascular risks associated with exposure to particulate matter are based on chronic exposure. Because costs were normalized to EAPP, the investment requirements found in Table 16 would need to occur every year.

Table 16: Annual Investment Cost to Prevent One Death from Cardiovascular Diseases Resulting from Exposure to Particulate Matter with Predictions Bounds. AVEARGE (LOWER BOUND; UPPER BOUND)

			Upesi	**Envirofit G3300**	**Philips Gasifier**
SCENARIO	**1**	**COFFEE/TEA**	**$9,000** ($8,800; $9,400)	**$8,400** ($8,300; $8,500)	**$6,500** ($6,100; $6,800)
	2	**SHORT MEAL**	**$5,400** ($5,200; $5,500)	**$5,500** ($5,400; $5,700)	**$7,200** ($7,000; $7,400)
	3	**SIMMERING**	**$4,800** ($4,700; $5,000)	**$5,000** ($4,900; $5,200)	**$7,400** ($7,200; $7,600)
	4	**COMMERCIAL**	**$9,000** ($8,800; $9,400)	**$8,400** ($8,300; $8,500)	**$6,500** ($6,100; $6,800)

After accounting for precision and significant digits, no difference existed in the cost to save a life between theoretical houses #1 and #2. A discussion on the differences and implications of homes of different sizes and air exchange rates can be found in subsequent sections.

4.3.2. Estimating Health Impacts of Biomass Cookstove Use

The level of improvement in human health achieved from a cookstove depends strongly on how the stove is used. As shown in Figure 32, the stove that resulted in the greatest cost/benefit changed with the situation. In some cases the low-cost Upesi would be in the best investment, while in others the ultra-clean Philips gasifier was superior.

Larger health improvements were found to occur in theoretical room #2 than room #1. Although perhaps counterintuitive, larger gains occurred in the large, open room due to the lower concentrations that occurred there. An incremental reduction in exposure at high concentrations has a lower reduction in mortality than would be found at already low concentrations due to the lognormal nature of the hypothesized dose-response curve (Figure 33). The shape of the curve indicates that a larger percentage improvement would occur by focusing on homes with high air exchange rates then small, tightly sealed homes. This is surprising, considering that small homes with low air exchange rates will have a higher overall mortality risk rate. These counteracting elements resulted in no significant difference in the predicted investment required to save a life.

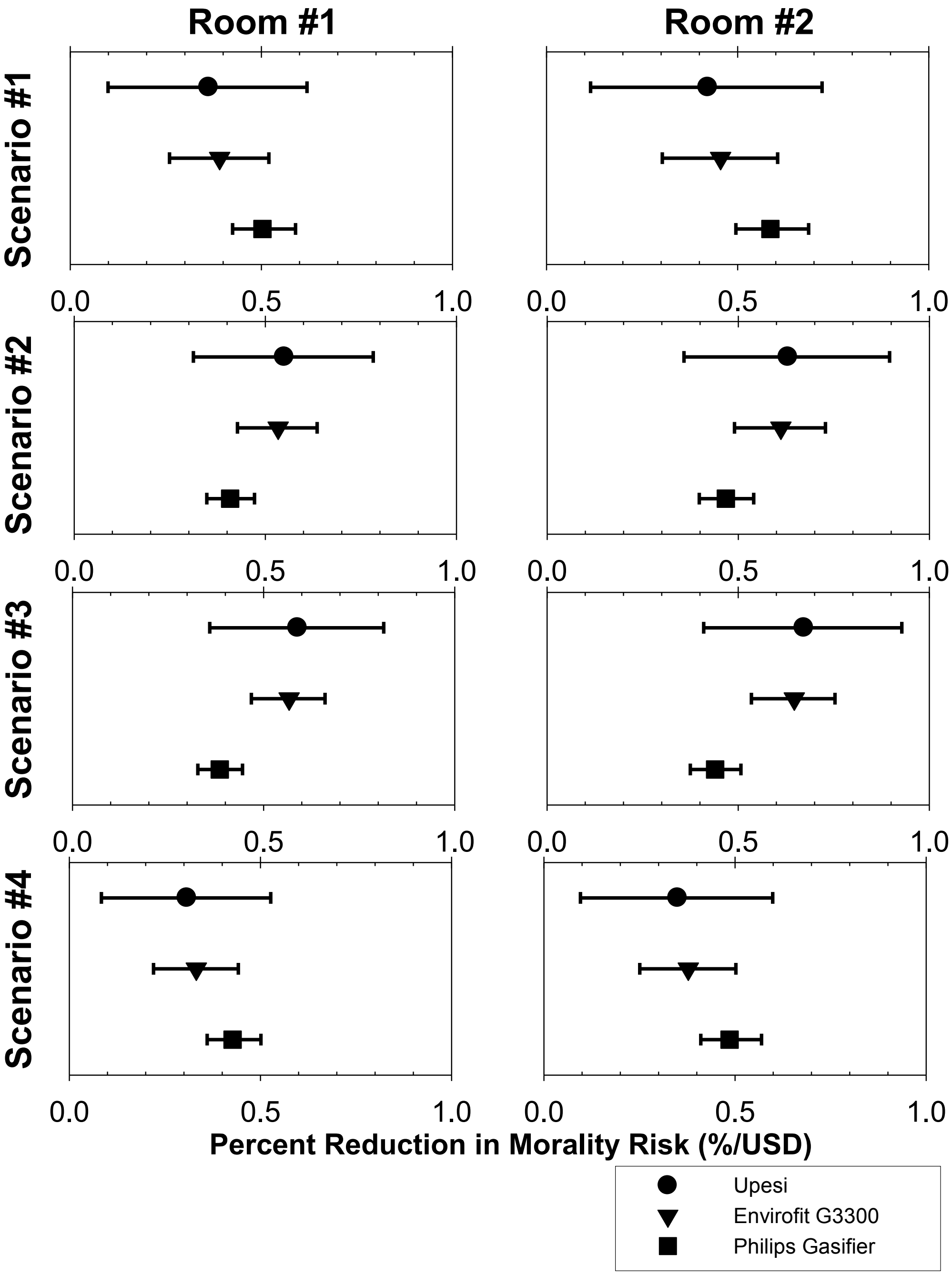

Figure 32: Percent Reduction in Cardiovascular Risk of Mortality Normalized by Equivalent Annual Purchase Price from a Three-Stone Fire. Bands represent best case and worst-case percent reductions

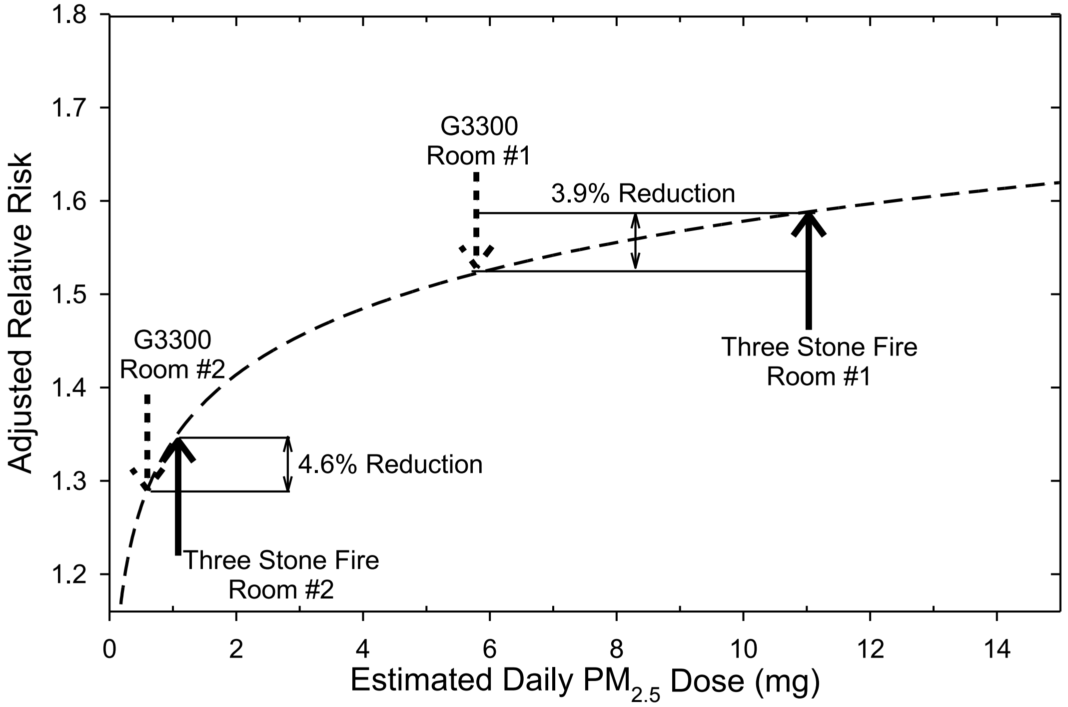

Figure 33: Adjusted Relative Cardiovascular Mortality Risk. Risks calculated for the three-stone fire and the Envirofit G3300 under scenario #1

4.3.3. Estimating Climate Impacts of Biomass Cookstove Use

The cost/environmental-benefit relationship of the improved cookstoves was more complex than initially anticipated. Despite the Philips gasifier having ultra-clean performance, the high capital cost of this stove results in the least impact (relative to each dollar invested) of the three cookstoves examined. For the simulations run, the Envrofit G3300 resulted in the greatest reduction in eCO_2, although there was a significant overlap in the performance bands. A tradeoff exists when selecting a cookstove for a program. Although the Philips gasifier resulted in the smallest reduction in eCO_2 production, it also had the smallest uncertainty. For some programs the security from these narrow bounds would outweigh the potential gains possible from other stove designs. Only one set of plots have been presented here because the total emissions emitted are independent of the location in which the stove is used.

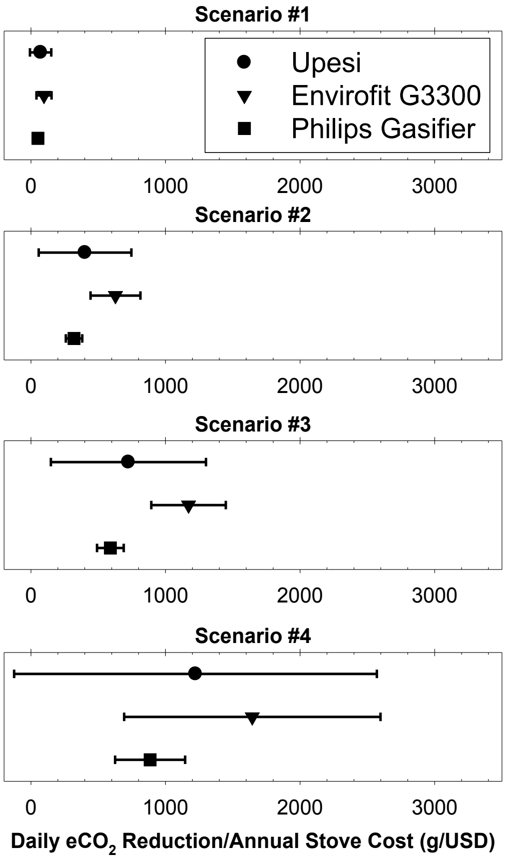

Figure 34: Reduction in Daily eCO2 Production for Four Theoretical Use Scenarios Normalized by Equivalent Annual Purchase Price from a Three-Stone Fire. Bands represent best case and worst-case percent reductions

4.3.4. Sensitivity Analysis

The effects of key model parameters on simulation results were evaluated through a series of sensitivity analyses (Table 17). The model was insensitive to locational factors such as room volume and air exchange rate. These results are consistent with the findings presented in Table 17; little difference occurs in theoretical room #1 due to the shallow dose/response curve at higher exposures. The model would be more sensitive to these parameters at lower exposures due to the log-linear nature of the dose/response curve.

Table 17: Sensitivity Study Model Parameters and Resulting Simulation Variation

Variable	Unit Change	Change in Mortality Risk/Stove Cost (%)	Change in eCO_2/Stove Cost (%)
Room Volume	+ 1 m^3	-0.3	Independent
Air Exchange Rate	+ 1 Exchange/hour	-1.2	Independent
Stove Cost	+ 1 USD	-17.4	-17.4
Stove Life	+ 1 Year	-100.0	-100.0
Inhalation Rate	+ 1 m^3/day	0.4	Independent
Mortality Regression Slope	+ 0.015 Risk/mg	136.3	Independent
Mortality Regression Intercept	+ 0.2 Risk	65.0	Independent
Global Warming Potenials	+1%	Independent	1.0

The model is highly sensitivity to the dose/response relationship. Researchers continue to investigate the relationship between exposure to biomass smoke and health and as our understanding of this relationship improves, the uncertainty will be reduced. Variations due to uncertainty in the regression intercept are independent of dose, while variations due to regression slope uncertainty change with dose (Figure 35).

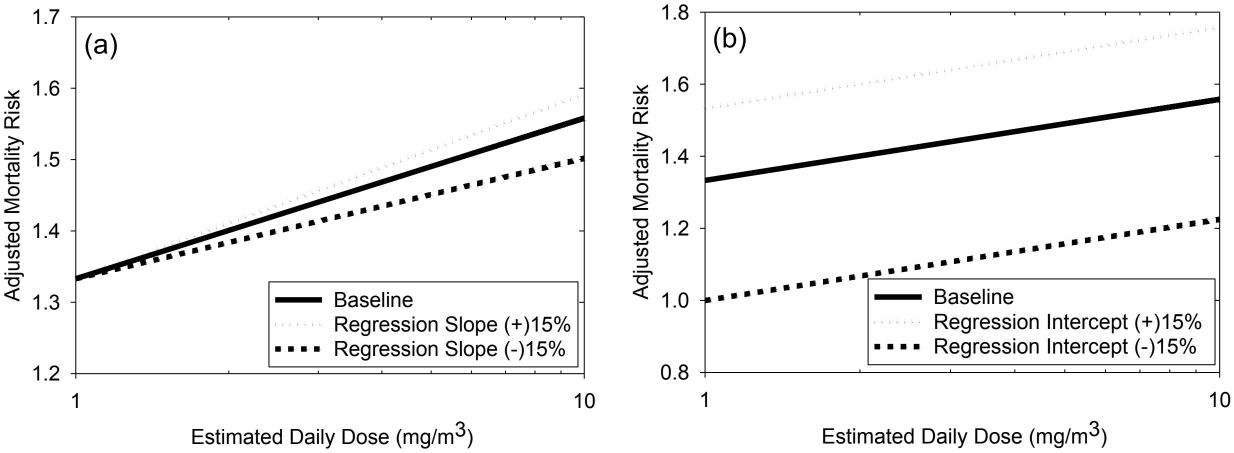

Figure 35: Impact of Varying Regression Slope (a) and Regression Intercept (b) on Predicted Adjusted Cardiovascular Mortality Risk

Stove cost and projected life can also have a major impact on model predictions. Although having reasonable values for these inputs is critical, they remain at the discretion of the modeler. The model could be used to evaluate possible intervention strategies prior to field trials as well as helping to quantify the impacts of programs that have already been implemented. One of the most significant contributions that the model can play in the cookstove sector is helping to compare the potential impacts from different cookstove designs and program options.

4.4. Comparison to Other Studies

The model predicted intervention costs similar to those found in previous studies. Many cost-effectiveness studies have previously been conducted linking air quality and health effects, including several specifically looking at cookstoves (130, 131, 132). Mehta et al. (130) analyzed cost-effectiveness for multiple biomass cookstove interventions. Although there are some differences in the methodology they use, the Mehta et al. study provided a good opportunity to evaluate the reasonableness of the model presented here. Mehta et al. used acute lower respiratory infection and chronic obstructive pulmonary disease (COPD) as metrics for health improvement. The study estimated that implementing a program capable of reducing exposure by 75% would cost between $3,000 and $33,000 per household. The study conducted by Mehta et al. included program costs as well as cookstove costs, whereas the model developed here only included cookstove costs. Although including programs costs is different than the calculations performed as part of the current analysis, the capital costs of the cookstoves were typically the majority of the total program costs in the Mehta et al. study (77.8% ± 27.9% of the total cost), making the results still useful for comparison. Although a number of differences exist between the method used here and that used by Mehta et al., the investment costs that would be required were comparable between the two studies. A critical difference between the two approaches is the inclusion of region-specific details. Mehta et al. considered various regions of the world but did not account for conditional variations between those regions. The model developed here accounts for the impact of different home conditions and cooking practices. The two studies seek to answer different but complementary topics.

4.5. Model Limitations and Future Model Developments

The study conducted here represents a best-case scenario and includes a number of assumptions, some of the major assumptions are discussed here. One of the major simplifications used in when estimating health risk is the simplified dose response curve. The dose/response curve used does not account for differences between individuals or differences between specific populations (such as children or pregnant women). The model also currently only considers cardiovascular mortality from particulate matter exposure, although numerous health pollutants and health risk pathways exist. The dose/response relationship for particulate matter remains an area of active research and more refined relationships are likely to be available in the future. Assumptions and simplifications were also required when quantifying climate impacts. A number of factors affect the potential carbon value of a cookstove. Such factors include how a fuel is harvested, how performance changes as a stove ages, and cookstove adoption rates. Carbon credit programs typically only assign monetary value to the eCO_2 generated from a non-renewable source. Fuels that are sustainably harvested or are waste products from another process are not eligible for consideration. If 75% of the fuel came from a renewable source, only 25% of the eCO2 is eligible for carbon credits. The study assumed that all fuel came from a non-renewable source, although the model is capable of accounting for renewable fuels.

The modeling technique presented here can be used to compare cookstove intervention options prior to undertaking costly and time intensive field studies. This approach allows for comparison of potential benefits from different cookstove design options quickly and economically in order to prioritize field evaluation efforts. Future work will seek to address some of the limitations of the current model:

- Refining Dose Response Curve: The sector’s understanding of the health effects of biomass cookstoves is constantly improving. Future modeling work will seek to incorporate more refined dose-response curves, including accounting for variability in inhalation rate based on activity levels.

- Time/Activity Budget and Personal/Ambient Concentrations: The model is currently limited by the assumption that an individual is exposed to the same concentration as the room as a whole. This is not a perfect assumption. People spend time outside of the home, and mixing inside the home is not perfect. Future work will seek to incorporate indoor micro-environments and allow time/activity budgets to be defined. Micro-environments will allow the model to calculate concentrations that are higher near the pollutant source (the cookstove) and lower around pollution sinks (open doors and windows). Time/activity budgets will define when an individual is near the cookstove, when they are in other regions of the room, and when they are outside the home. Incorporating these components will increase the accuracy of the model, but will also inherently require more detailed information on cookstove use.

5. Conclusions and Next Steps

There is a need for improved biomass cookstoves around the world. Improved cookstoves have the potential for numerous benefits. However, despite the large potential market, the numerous benefits, and decades of work in the sector, we rarely determine whether improved cookstove programs are effective and impactful. This is not just due to a lack of knowledge or data, but an inability to evaluate the information that does exist systematically. There has not been a technically robust manner of using the data and information that is currently available in the sector and putting it into a usable form. The work presented here is a first step towards improving our understanding of biomass cookstove performance and impact. The work has sought to illustrate the limitations with the methods currently being used, outline a method that addresses these limitations, and then to demonstrate the potential of numeric methods for prediction the impact of improved biomass cookstoves.

5.1. Uncertainty Associated with Field Testing of Cookstoves

Field testing is, and will always be, a critical component of biomass cookstove programs. Field testing provides information that cannot be gathered in any other manner, such how and where the cookstoves are used, what people want or need in a design, and if new designs meet the needs of the customer. However, field testing also has a number of fundamental limitations including inherent variability. The variability associated with field testing complicates the performance quantification and limits our ability to define impact at personal, local, and national levels. Although some of the factors related to field test variability can be managed, many factors are intrinsic to field tests. The cookstove sector needs to re-evaluate how and why field testing is conducted and consider alternative methods of gathering much of the data for which field tests are often used. For the field tests that are conducted an increased appreciation for the variability that will exist in the results is needed. Field testing results are going to have highly variable results that may not be an indication of the cookstove, or the study, but a reality of field testing. Because of the variability seen from field tests, it is important that programs budget for enough test replicates and that the teams conducting the tests are capable of handling the complexity of field testing.

5.2. The Use of Numerical Models for Evaluating Cookstove Impact

Numerical models have the potential of addressing some of the limitations of field testing. Where evaluating a cookstove in the field can cost hundreds of thousands of dollars and take months of research, the impact of that cookstove could be predicted for numerous countries and situations in a single day with a numerical model. In order to gain acceptance, numerical modeling needs to be simple yet representative of reality. A major component of usable models is practical and reliable ensuring that the data needed for inputs can be collected in a practical manner. Case studies have demonstrated that the model developed here could generate realistic results (both for performance and distribution) using existing data that has already been collected by many such programs.

5.3. Demonstration of the Potential for Numerical Models

One of the many challenges with biomass cookstoves is objectively comparing their performance. Mass emissions rates alone are not sufficient. Quantifying cookstove performance and their impact requires considering how and where a cookstove is used. This is where numerical modeling can play a critical role in the cookstove sector. It is not practical or feasible to conduct field tests in every location and for every situation, however it is simple for models to evaluate these different situations. By defining the performance of different cookstoves and the conditions in which they might be used, it becomes simple to objectively determine the ideal cookstove for a given situation.

5.4. Future Work

Despite the promising results of the model to date, this is only the surface of the potential for numeric models in the cookstoves sector. Suggested future work has been broken into several broad categories:

5.4.1. Model Refinement

- Use Pattern: The current model only uses three operating conditions. The performance and accuracy of the model could be improved by expanding the resolution that is being used. Two major conditions that should be considered are stove start-up and smoldering. Although these phases may only represent a short amount of time during the day, they may account for a significant portion of the emissions released.
- Laboratory/Field Connection: The model currently only considers a few external factors that affect the emissions rate of cookstoves. A better understanding of the differences that exist between the emissions rate of a cookstove in the field and the highly repeatable results of laboratory testing is needed. These secondary factors could be used to improve the predictive power of the model.
- Personal/Ambient Concentrations: The model currently assumes that an individual's exposure is the same as the room's concentration, which is not an ideal assumption. The average concentration inside the room is not the same as the microenvironment around the cook.

5.4.2. Model Expansion

- Use Pattern: The model currently relies upon matching how a cookstove is operated (i.e. high power vs. low power). The model could be improved by alternatively looking at how the cookstove is used. One approach is to include heat transfer components that are matched to cooking tasks, for example heating a pot and simmering for a set amount of time.
- Time/Activity Budget: Inclusion of time/activity budgets would allow the option of defining where the user is at different times. Time/activity information would allow adding exposure that occurs when the user is outside the home and different exposures depending on the cooking task that is currently occurring.
- Impact Factor: There are numerous potential benefits of using improved cookstoves that were not considered in the current model, such as reduced drudgery and job creation. There is the potential

of evaluating the ability of a cookstove to improve these conditions. These other potential benefits of using improved cookstoves preset different challenges than the factors currently considered in the model as some factors, such as drudgery, do not inherently have a numeric value. Benefits that are difficult to enumerate could be considered by assigning “impact factors.”. One example of an impact factor would be to assign a score for reducing the time required to collect wood. Only reducing that time a little would have a low impact factor whereas a large reduction would have a high impact factor.

5.4.3. Specific Studies

- Target Market for Specific Cookstove Designs: The modeling approach presented here has the potential to evaluate cookstove designs across different markets. Cookstoves are often designed without a specific country or region of use in mind. Some very interesting data could be gathered by considering a few cookstove designs that are already in the marketplace and simulating their use in different regions of the world. Such a study could identify where major impact could be achieved. Resources could be used more effectively by targeting regions with the greatest potential for impact.
- Program Design: The model could be used to design the “optimum” cookstove for a particular region of the world. By considering the specifics of a given region, the model may aid in determination of optimized cookstove characteristics.

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