BIOMASS AND BIOENERGY XXX (2014) 1–9

Available online at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

# A quantitative model of cookstove variability and field performance: Implications for sample size

Christian L'Orange [a,*], David Leith [b], John Volckens [a,c], Morgan DeFoort [c]

[a] Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, CO 80524, USA
[b] Department of Environmental Sciences and Engineering, University of North Carolina, Chapel Hill, NC 27599, USA
[c] The Energy Institute, Colorado State University, Fort Collins, CO 80524, USA

ARTICLE INFO

*Article history:*
Received 11 April 2014
Received in revised form
28 October 2014
Accepted 30 October 2014
Available online xxx

*Keywords:*
Biomass
Uncertainty
Numerical model
Sample size
Field testing
Wood combustion

ABSTRACT

Many cookstove studies conducted in the field fail to measure meaningful differences between different stove technologies. Although meaningful differences do not always exist, significant differences are often missed because of low statistical power. A numerical model has been developed to determine the minimum sample size necessary to ensure that cookstove field studies are well-designed, efficient, and have adequate statistical power to characterize the concentrations of pollutants inside homes. The numerical model uses a Monte Carlo prediction method to generate probabilistic distributions of indoor pollutant concentrations. The model is based on a series of user inputs, including emissions rate, home size, air-exchange rate, fuel-moisture content, and measurement error. Application of this model to an example situation showed that, even under optimistic measurement conditions, a substantially high number of test replicates would be required. This approach should allow organizations to select appropriate sample sizes to test cookstoves in the field and to identify factors that contribute to variability among tests.


## 1. Introduction

Improved biomass cookstoves are needed as emissions from traditional cookstoves often have detrimental health and climate effects [1–4]. As nearly three billion people currently use biomass cookstoves, the cookstove problem will require global initiatives and collaborations among many organizations. To help facilitate these collaborations, new testing protocols and standardized practices for sharing data have recently been adopted. One example is the International Workshop Agreement (IWA 11:2012), which was developed through the International Organization for Standardization (ISO) to help rate and compare cookstoves [5]. Discrepancies are often seen between evaluations of cookstove performance conducted in the laboratory and those evaluated in the field. Thus, there is concern that new cookstove designs are not achieving the goals of improving health and climate. As part of the IWA, a resolution was passed to prioritize research that seeks to harmonize laboratory-based evaluations with field evaluations of cookstove performance.

The goal of the IWA field-testing resolution is to ensure that improved cookstove designs, many of which have been designed in the laboratory, actually release fewer harmful emissions than traditional designs. Evaluating cookstoves in the field presents many challenges, including determining the

* *Corresponding author*. 430 N. College Ave, Fort Collins, CO 80524, USA. Tel.: +1 970 491 4793; fax: +1 970 491 4799.
E-mail address: christian.lorange@colostate.edu (C. L'Orange).
http://dx.doi.org/10.1016/j.biombioe.2014.10.031
0961-9534/

number of test replicates required. A sufficient number of replicates is needed to determine if meaningful differences exist between different stoves. However, an unnecessarily large sample size consumes program resources and may not provide additional useful knowledge [6].

Every cookstove program will have an upper limit to the number of test replicates they can collect. The limitation may be due to cost or practicality, but every project will have a limit. As sample size increases so does personnel needs, time requirements, and study cost [6]. Although what a program can afford (time wise and financially) to devote to field testing is project specific, with increasing sample size fewer and fewer programs will have the resources needed for the study.

The sample sizes used by cookstove programs are often determined by power calculations or general "rules of thumb." Power calculations are conducted by setting a target level of precision and an estimation of the variability between test replicates to determine the sample size. Sample size "rules of thumb" are typically generated by power calculations based on assumptions regarding the level of confidence required and the variability expected for the type of testing to be conducted. The World Health Organization and the Gold Standard Foundation are examples of organizations that calculate sample sizes by "rules of thumb" [7,8].

Although "rules of thumb" are convenient for determining sample size, they are often based on assumptions that do not translate uniformly to the field. The accuracy of power calculations is also limited by an understanding of the environmental factors that affect stove performance variability. These factors vary greatly and include properties such as room size, air exchange rate, and cultural cooking practices. Although using "rule of thumb" statistical methods at first appears convenient, as demonstrated by Edwards et al. determining an appropriate sample size using this approach is far from simple. Choosing a study design and sample size requires investigators to make a number of assumptions, best-guess estimates, and hard choices [6].

The objective of this work was to develop a user-friendly method to inform the proper design and implementation of cookstove field studies. A recent study published by Wang et al. investigated sample size requirements when testing cookstoves in laboratory settings. This study clearly demonstrated the large variability in cookstove performance results even under highly controlled environments [9]. As discussed in the previously mentioned article, even highly controlled tests conducted in sophisticated labs have sources of variability which cannot be eliminated. The sources of variability only increase when testing in the field. The model developed here extends the sample size calculations by considering the effects of cultural cooking practice, home size, and cookstove design to allow a more accurate prediction of performance variability and the number of test replicates required to achieve statistical confidence when evaluating biomass cookstoves in the field.

### 1.1. *Basis for the model*

Many factors influence the concentrations of air pollutants produced by cookstoves [9]. Therefore, to estimate the required number of test replicates, the major sources of variability that affect stove performance must be considered.

- Stove variability: The age and condition of a cookstove can affect performance; every cookstove is unique. Minor differences in construction can affect performance as well as age of a cookstove. Therefore, two stove units of the same design may perform slightly differently, even if construction and quality control measures are standardized.
- Fuel variability: Biomass combustion is a complex process. Small differences in the condition or composition of fuel can have a large effect on emissions. Many fuel characteristics, including aspect ratio, surface area, moisture content, and fuel type or species, affect cookstove performance [10].
- User variability: The user has a large influence on the performance of a cookstove. For example, an individual who is familiar with a particular cookstove will operate it differently than a first-time user [11,12]. Large variability will also occur for the same user day to day. In the field, users often will perform multiple cooking tasks all on the same stove; often these different cooking tasks require different operating conditions.
- Situational variability: Situational variability encompasses many components related to the location at which a stove is tested. The concentration of pollutants that accumulate in a room depends on the size and shape of the room and the airflow through the room, which depends on the number of open doors and windows [13,14].
- Measurement errors: Although errors in sample measurement do not affect stove performance variability, they do contribute to the inaccuracy and imprecision of data collected in the field. Errors in measurement include systematic and random errors. An inaccurate but consistent measurement is an example of a systematic error, which leads to biased results but not necessarily increased variability between tests. Random errors (in the context of measurement) arise from the imprecision of an instrument or variable measurement readings. An increased number of replicates can reduce imprecision due to random errors [15].

These factors interact in a complex fashion that complicates field-based measurements of biomass cookstove performance. However, because these factors (and their interactions) are stochastic in nature, they may be modeled numerically. Monte Carlo is an attractive method for modeling biomass cookstove performance, as it accommodates complex interactions between various input variables. The Monte Carlo method has been applied to many fields and disciplines, such as synaptic signaling in the brain [16] and economic planning [17].

Monte Carlo simulations are typically comprised of three elements (Fig. 1). First, equations are established for basic interactions in the system, such as how emission rate affects pollutant concentrations inside a home. Second, key parameters of the model are defined as distributions, such as the range of home sizes in a particular community. Finally, a distribution of outputs is created by randomly selecting values

Please cite this article in press as: L'Orange C, et al., A quantitative model of cookstove variability and field performance: Implications for sample size, Biomass and Bioenergy (2014), http://dx.doi.org/10.1016/j.biombioe.2014.10.031