MAXIMIZING CLIMATE AND HEALTH BENEFITS IN HOUSEHOLD ENERGY CARBON CREDIT PROJECTS

by

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ABSTRACT

‘Improved’ cooking technologies, which in general are cleaner burning with higher levels of complete combustion, greater efficiency and better heat transfer then less-efficient cooking technologies, have been generally understood in the global community to be a ‘win-win’ development intervention creating a multitude of benefits. Yet as in most environment-development efforts there are many unacknowledged tradeoffs that exist under the all-encompassing ‘win-win’ claims. In this study tradeoffs made between two co-benefits of cookstove projects, climate and health, are examined under the framework of carbon financing mechanisms. Two methodologies used to calculate carbon credits for cookstove projects are compared, the Gold Standard method and the Clean Development Mechanism method. Different carbon credit scenarios are evaluated for how they compare to estimated health impacts when switching from a traditional biomass stove to each of the other ten alternative stove-fuel combinations including three basic improved biomass stoves, two gasifying biomass stoves, two coal stoves, one charcoal stove and two liquid fossil fuel stoves. Tradeoffs between the maximization of co-benefits were found to exist, with carbon credits inherently accounting for climate benefits, but not health.

The three stove types achieving the highest levels of co-benefits were the two liquid fossil fuel fueled stoves included in the analyses, kerosene and liquid petroleum gas, and a more technologically advanced gasifying biomass stove with a battery powered fan. Yet they were also the most expensive and the fossil fuel stoves were treated very differently in the two methodologies, creating a diffusion barrier to achieve the highest maximization of co-benefits.

The Gold Standard methodology consistently calculated more carbon credits than the Clean Development Mechanism, largely due to its inclusion of methane emissions in its calculations. Including black carbon emissions in theoretical carbon credit calculations also significantly increased the number of credits calculated. If accounted for in such equations this could greatly increase the amount of income earned per project as well as change how such projects are designed and approached due to the large increase in potential credits calculated. As health and other development benefits are not inherently included in carbon credit calculations, in order to achieve 'win-win' outcomes, deliberate decisions about project design need to be made to ensure such objectives are actually met and not simply assumed.

PREFACE

The research in this thesis will be published in two peer-reviewed articles. Both will be co-authored by my supervisor, Dr. Hisham Zerriffi and me. The first is based on the literary review included in the *A Review of the Literature* section. The second covers the main research material in this thesis. The conceptual idea for this research was proposed by Dr. Hisham Zerriffi. I carried out the literature review and analyses under Dr. Hisham Zerriffi's supervision. I wrote the manuscripts for both papers and Dr. Hisham Zerriffi contributed towards the revision of both in preparation for publication.

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LIST OF ACRONYMS

ALRI	Acute Lower Respiratory Infections
BC	Black Carbon
CER	Certified Emission Reduction
CDM	Clean Development Mechanism
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
CVD	Cardiovascular Disease
EF	Emission Factor
***f*NRB**	Fraction of Non-Renewable Biomass
GHGs	Greenhouse Gases
GS	Gold Standard
GWP	Global Warming Potential
IAP	Indoor Air Pollution
IPCC	Intergovernmental Panel on Climate Change
LPG	Liquid Petroleum Gas
N_2O	Nitrous Oxide
NGO	Non-Governmental Organization
NMHC	Non-Methane Hydrocarbons
NO_x	Nitrogen Oxide
OC	Organic Carbon
PICs	Products of Incomplete Combustion
$PM_{2.5}$	Particulate Matter Equal to or Smaller than 2.5 Microns in Diameter
PM_{10}	Particulate Matter Equal to or Smaller than 10 Microns in Diameter
SO_2	Sulfur Dioxide
tCO_2e	1 Tonne of CO_2 Equivalent
VER	Voluntary Emission Reduction
WBT	Water Boiling Test

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1 INTRODUCTION

On the surface, using carbon credits to fund the diffusion of improved cooking technologies in the developing world would seem to be an appealing approach to mitigating two of the grand challenges facing the world today: climate change and the negative health impacts from indoor air pollution (IAP) resulting in approximately 1.3 million premature deaths annually in low-income countries and 2 million globally[1] (Mathers et al., 2009). Roughly 3 billion people globally rely directly on inefficiently burning solid materials like wood, charcoal, dung and coal to meet their daily cooking needs (Legros et al., 2009). On the one hand this has direct environmental effects ranging from emissions of greenhouse gases (GHGs) to pressures on local forest resources. On the other hand, indoor emissions creating major health impacts and the need to spend time and energy collecting fuel that could be productively used otherwise makes this a major development problem. Cookstoves projects that can reduce or eliminate solid fuel use, reduce indoor emissions and reduce GHG emissions are framed as 'win-win' projects and have gained traction globally as of late. This includes increased international investment in pro-poor cookstove companies and organizations, the creation of the international public-private partnership, the Global Alliance for Clean Cookstoves[2], which has the ambitious goal to provide 100 million households with improved cooking technologies by 2020, and the opportunity to apply for carbon credit

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[1] Due to the burning of solid fuels only. Globally the impacts are experienced in middle- and low-income countries only (based upon countries categorized by gross national income per capita- low-income: US$825 or less; middle-income: $825-$10.066 (Mathers et al., 2009)).

[2] http://www.cleancookstoves.org/ [Accessed: September 1, 2012]

funding. In the case of carbon credits, cookstove projects are viewed as being one of the few projects directly promoting sustainable development through the incremental, direct development and climate benefits they can create simultaneously (Bumpus, 2009; Simon et al., 2012; Peters-Stanley and Hamilton, 2012).

As is the case in other development-environment initiatives framed as ‘win-win’ there are inherent tradeoffs made between potential benefits or ‘wins’, sometimes creating ‘winners’ and ‘losers’ (McShane et al., 2011; Simon et al., 2012; Tailis et al., 2008). In an analysis of World Bank projects with dual environmental and development objectives only 16% were found to effectively address both (Tailis et al., 2008). In the case of cookstoves, Simon et al. (2012) state that some of the challenges with implementing carbon financed cookstove projects can result in mutually supported impediments. For example the large scale at which such projects need to be implemented to be profitable can make the already existing development challenge of providing appropriate uptake of technology on a local, long-term scale an intensified impediment for project success.

Though there can be overall improvement in many potential benefits of development-environment initiatives, some benefits may be preferentially privileged over others. Therefore the term ‘win-win’ contains many subtle nuances often not explicitly recognized or addressed. The seduction of ‘win-win’ initiatives presents the danger of development-environment initiatives resulting in varied performance with unacknowledged tradeoffs.

Drawing on the literature and three cookstove specific case studies Simon et al. (2012) provides an overview of such ‘win-win’ nuances for carbon financed cookstove projects. They stress that ‘win-win’ climate and development benefits are not automatically achieved through carbon financed cookstove projects. Of particular importance, the definition of ‘win-win’ can have direct implications on outcomes of such projects influencing who benefits and how. Focusing mainly on development benefits more generally, they do not compare specific tradeoffs between the maximization of health and climate benefits, mentioning only that health benefits are incrementally created along with climate benefits. While this is the case in many scenarios, there are tradeoffs that exist between the maximization of health vs climate benefits; some stoves are optimized to reduce GHGs while others are better at reducing exposure to particulate matter, resulting in higher health benefits (Grieshop et al., 2011).

This research addresses the knowledge gaps that exist, specifically focusing on tradeoffs between the maximization of climate and health benefits for cookstoves in the context of carbon credit markets. As carbon credit programs provide large potential to help fund cookstove initiatives and the number of applications for cookstove carbon credit projects continue to increase (Blunck et al., 2011), implications of carbon credit certification on health outcomes is salient.

Additionally this research examines some of the specifics in the calculations of carbon credits, comparing two different methodologies, the Clean Development Mechanism (CDM) and the Gold Standard (GS), and exploring the impact on carbon credits calculated when a more extensive set of climate forcings are included in the calculations. Both of these have a large impact on how climate benefits are represented in cookstove carbon credit projects, which are then compared with health benefits. Potential tradeoffs are examined in three main areas: the choice of carbon credit methodology, methodological considerations within the calculations, and how overall health and climate benefits of carbon credit cookstove projects compare for the different types of cookstoves included in this study.

Through these analyses, this work touches on debates about the technicalities of carbon accounting, integration of measures for promoting sustainable development through carbon credit projects, and some of the benefit tradeoffs involved in implementing cookstove projects under a carbon credit framework. The aim is that the findings from this research provide informative material that can be taken into consideration in the future implementation of carbon credit cookstove projects.

2 A REVIEW OF THE LITERATURE[3]

2.1 Overview

To compare the relative climate and health benefits of different cookstove scenarios under the carbon credit framework a summary of relevant concepts and previous work are presented. In this section the following areas are reviewed:

- the definition of an 'improved' cookstove and the corresponding potential benefits;
- the climate and health implications resulting from cookstove emissions;
- an introduction to carbon credits and the two different carbon credit methodologies cookstove projects can become certified under;
- some methodological concerns in the current cookstove carbon credit methodologies including the extent to which climate forcings are represented;
- the two estimates of potential health benefits created by 'improved' cookstoves employed in the analyses;
- previous work looking at tradeoffs between climate and health benefits in cookstove projects;
- additional tradeoffs involved in actual cookstove project implementation;

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[3] This section draws on work from two manuscripts that are being prepared for publication. Sections 2.2, 2.3, part of 2.6, 2.7 and 2.8 draw on work written for publication in the *Forestry Chronicle*. This paper has been accepted, but not yet published. Sections 2.4, 2.5, part of 2.6 and 2.9 are from a manuscript under preparation to be submitted to a peer-reviewed publication after completion of the thesis. The rest of the material in this document from the methods section on draws directly from the same work written for the second publication.

- and finally the knowledge gap which is addressed in this study is identified.

2.2 'Improved' Stoves and Their Benefits

Nearly half of the wood harvested globally is used as fuelwood (FAO, 2002). More than 3 billion people rely on some form of solid fuels (traditional biomass, charcoal and coal) to meet their cooking and heating needs almost all of which are in developing countries, the largest concentrations of users living specifically in Asia and sub-Saharan Africa (Legros et al., 2009). A large percentage of these households still rely on some form of traditional stove to meet these needs, as only 828 million people use an 'improved' cookstove on a daily basis, more than two-thirds of which live in China (Legros et al., 2009).

An 'improved' cooking technology is a term that is used liberally[4]. It usually refers to a stove with increased efficiency, more complete combustion, and better heat transfer.[5] This corresponds to a decrease in fuel use, and decreased emission of products of incomplete combustion. As a result, switching from a traditional[6] or less efficient cooking technology to an improved cooking technology has long been considered a 'win-win' development project due to the co-benefits that can result

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[4] See Smith and Dutta (2011) for discussion about the appropriateness of the word 'improved' to describe cleaner cooking technologies.

[5] Some literature distinguishes between 'improved' cookstoves that continue to burn solid fuels, only more efficiently and cleanly, and 'modern' fuels and technologies, such as electric stoves, liquefied petroleum gas (LPG) and biogas stoves that avoid using solid fuels in the household entirely. Here such distinction is not made with both types of stoves referred to as 'improved'.

[6] Traditional cookstoves include 'three-stone' fires and hand built mud stoves. Both are characterized by inefficiency and generation of smoke.

(Barnes et al., 1993; Smith and Haigler, 2008; Simon et al., 2012). The benefits of transitioning to this technology can include all three major components of sustainable development, social, environmental and economic benefits:

- **Social benefits** (Mostly impacting women and children): reduction of IAP (Bruce et al., 2000; Smith et al., 2000c; Smith and Mehta, 2003; Rehfuess, 2006), reduced physical burden and risk associated with fuelwood collection (Patrick, 2007, Wickramasinghe, 2003; Matinga, 2008), empowerment of women (Rehfuess, 2006; Parikh, 2011)
- **Environmental benefits**: decreased pressure on fuel resources (e.g. woody biomass) (Barnes et al., 1993; Rehfuess, 2006), reduction of climate forcers emitted (e.g. GHGs) (Bond et al., 2004; Smith and Haigler, 2008; Grieshop et al., 2011)
- **Economic benefits** (See Barnes et al., 1993; Hutton et al., 2006: Rehfuess, 2006): reduced expenditures (if paying for fuel), time savings, increased productivity, decreased health costs, potential engagement in other economic generating activities, job creation

However, significant barriers remain for diffusing both improved solid fuel stoves and more modern fuels and technologies for cooking, including major cost impediments for the primarily poor and rural populations using traditional stoves.

Though people have been improving and experimenting with cooking technologies for centuries, global interest in investing in such programs through non-governmental organizations (NGOs) and governmental channels first occurred in the 1970's (Barnes et al., 1993). This was born out of the concern about world energy supply and perceived rates of deforestation (Barnes et al., 1993; Top et al., 2004; Elias and Victor, 2005). Hundreds of improved cookstove projects have been implemented since then with the rationale for implementing such cookstove projects shifting from focusing on relieving pressure on biomass resources to the combination of development and environmental benefits that can be generated (e.g. Bailis et al., 2005; Elias and Victor, 2005; Hutton et al., 2006; Smith and Haigler, 2008; Simon et al., 2012).

There also now exists extensive literature about various aspects of cookstoves including: estimation of both development and environmental benefits (e.g. Mehta and Shahpar, 2004; Hutton et al., 2006; Smith and Haigler, 2008), scientific analysis of aerosol emissions (e.g. Zhang et al., 2000; Roden et al., 2006; Jetter and Kariher, 2009), impacts on health (e.g. Bruce et al., 2000; Smith et al., 2000c; Smith et al., 2009b), critical analysis of project implementation (e.g. Smith et al., 1993; Hanbar and Karve, 2002; Sinton et al., 2004; Bumpus, 2009; Troncoso et al., 2011), analysis of diffusion business models (e.g. Shrimali et al., 2011; Zerriffi ,2011; Chaurey et al., 2012), and factors influencing adoption of new technologies (e.g. Bailis et al., 2009; Pine et al., 2011; Ruiz-Mercado et al., 2011; Wickramasignhe et al., 2011).

2.3 Products of Incomplete Combustion: Health and Climate Implications

Incomplete combustion during the use of cookstoves results in the emission of products of incomplete combustion (PICs), which have implications for both climate and health. PICs consist of: inorganic gases (e.g. carbon monoxide (CO), nitrous oxide (N_2O)), hydrocarbons (e.g. non-methane hydrocarbons (NMHC)), oxygenated organics (e.g. organic alcohols), and particulate matter (inhalable (PM_{10}), respirable and fine particles ($PM_{2.5}$)) (Naeher et al., 2007). Nominal combustion efficiencies of cookstoves range from 80-99% depending on the type of fuel and stove that is being used (Smith et al., 2000b).[7] The higher the nominal combustion efficiency the less emission of PICs.

The health impacts of the exposure to PICs are commonly quantified by measuring the amount of PM_{10} or $PM_{2.5}$, that is, particulates equal to or less than 10 or 2.5 microns in aerodynamic diameter (Sinton et al., 2004; Naeher et al., 2007; Grieshop et al., 2011). The constituents of particulate matter includes components which can be detrimental to health while also having climate implications (Smith et al., 2009a). In particular, organic carbon (OC) and sulfates are both climate cooling, while black carbon (BC) has significant warming effects (Smith et al., 2009a).

While health benefits are mainly estimated by the reduction of particulate matter emitted, potential climate benefits are determined by the emissions of specific PICs and reduced fuel use. Additionally, different cooking fuels have different climate benefits associated with them. For example, charcoal and fossil fuels (including coal)

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[7] This should not be confused with the efficiency of heat transfer or the total energy efficiency of combustion, which can be well below 20% for traditional stoves. Where *nominal combustion efficiency* is the amount of chemical energy in the fuel that is released as heat, *heat transfer efficiency* is the amount of heat that is transferred to the pot and *total energy efficiency of combustion* or *thermal efficiency* is overall efficiency of the stove integrating both nominal combustion efficiency and heat transfer efficiency values together.

have upstream and transportation emissions associated with their use. Charcoal production specifically has high amounts of GHG emissions even though it burns relatively cleanly with minimal emissions of PICs compared to other biomass fuels (Bailis et al., 2005; Grieshop et al., 2011). Biomass, if harvested at a renewable rate can result in zero net emissions of carbon dioxide (CO_2), though there are additional climate impacts from other climate warming PICs emitted during combustion such as methane (CH_4) and BC. In general, the cleaner burning the fuel, the higher the combustion efficiency, and the less fuel used for a given cooking task, the less climate-forcing and health-damaging PICs emitted. This can result in the creation of benefits for both health and climate, but the amount of different benefits varies with each specific technology.

2.4 Carbon Credits: How They Work

The carbon market was developed to address concerns about climate change by providing an economic mechanism to incentivize the reduction of CO_2 and other GHGs emitted. Carbon credits are tradable units that represent the reduction of 1 tonne of CO_2 equivalent (tCO_2e) that can be used to offset emissions. They can be bought and sold in two types of carbon markets, the regulated and the voluntary markets. Cookstove projects are one of the many projects that can become carbon credit certified when switching from the baseline to project stoves based upon the amount of non-renewable fuel that is reduced and in some cases also based upon their reduction of emissions of GHGs. Currently there are two main methodologies by which cookstoves projects are certified to sell carbon credits: the CDM method (UNFCCC, 2011d) and the GS method (The Gold Standard, 2011b).

The CDM is an instrument built into the internationally negotiated treaties to reduce greenhouse gas emissions (the United Nations Framework Convention on Climate Change and subsequent Kyoto Protocol). It accredits emission-reduction projects in developing countries with certified emission reductions (CER) credits, which can be sold on the regulated market (e.g. European Emissions Trading Scheme). Industrialized countries with commitments under the Kyoto Protocol can buy these credits to offset their emissions in the most cost-efficient manner (UN, 1998; UNFCCC, 2011a). At the same time, developing countries that produce credits are supposed to gain some development benefit from the project as determined by the Designated National Authority (DNA) within the country. Since the standards between the DNAs in countries can differ, this dearth of consistency results in highly varying sustainable development outcomes. Due to the lack of strong and unified efforts to realize development benefits alongside emission reductions, the CDM has been criticized for not addressing the sustainable development component of their mandate (For a review of the literature: Olsen, 2007; Also see Bumpus and Cole, 2010; Cosbey et al., 2005; Figueres, 2006; Pearson, 2006; Sterk and Wittneben, 2006).

In comparison, the GS framework aims to provide higher levels of sustainable development than those carbon credits accredited under other methodologies such as the CDM. To achieve this they limit the scope of acceptable project types (The Gold Standard, 2011c), make conservative baseline estimates and additionality evaluations (Drupp, 2011; The Gold Standard, 2011c), and require stakeholder participation, environmental impact assessments, and the use of their sustainable development matrix (The Gold Standard, 2011c). This strong commitment to sustainable development outcomes in addition to emission reductions is attractive to many different types of buyers and, in theory, earns a premium on the market.

The GS framework can be used to certify both CERs for the regulated market or voluntary emission reduction (VER) credits. VER credits are sold and traded in an unregulated carbon market to individuals, socially-responsible companies/corporations and other actors without regulated emission reduction commitments. The GS CER credits are jointly certified under the CDM and GS using CDM calculations and methodology, but requiring the extra steps in GS certification to ensure a higher quality credit. This can result in the GS CER credits being sold at a 5-25% higher price than CER credits alone (Drupp, 2011). The VER credits are calculated using a GS developed methodology, which has a number of significant differences in comparison to the CDM methodology. In this study when the GS method is referred to, it is referring to the methodology for calculating GS VER credits.

In 2011, cookstove projects made up 4% of total VER credits sold. These projects are relatively new in the market and due to the perceived 'win-win' nature of the projects, fetched the highest average price of all VER project types, higher than the average GS project price and approximately $4 below the average price for CER credits (See *Table 1*) (Peters-Stanley and Hamilton, 2012). As future investment in carbon markets are still uncertain, the current trends may change. Still cookstove credits are comparatively highly attractive to buyers, specifically in the voluntary market as, "…the high price not only reflects the cost to implement and maintain the projects, but also corporates' desire to support projects with community health and other social benefits" (Peters-Stanley and Hamilton, 2012). Specific prices for cookstove projects CER credits and the difference in price between average CER and average CER GS credits were not available for this analysis.

Table 1 Price of VER and CER credits in 2011: all project types vs GS projects vs cookstove projects. Specific prices for CER GS and cookstove projects were not available. Prices were taken from: Peters-Stanley and Hamilton (2012).

Average Prices in 2011

	All Projects	**GS Projects**	**Cookstove Projects**
VER	$6.20	$10.40	$13
CER	$17.38	N/A	N/A

2.5 Carbon Credit Calculations

For carbon financing to uphold its integrity, it is crucial there are accurate carbon accounting methods representative of actual emission reductions. Although the GS method provides a more detailed calculation of emission reductions by including more extensive descriptions about input measurement and monitoring procedures (The Gold Standard, 2011b), both CDM and GS methodologies have been criticized for lacking scientific rigor to accurately calculate the amount of emission reductions (Johnson et al., 2010; Bumpus, 2011; GACC, 2011).

The costs of acquiring measurements of variables rise with accuracy. A current challenge is determining an acceptable amount of uncertainty in calculations while not requiring such costly procedures that inhibit the ability of cookstove projects to apply for carbon credits. In both CDM and GS cases, the methodology for the measurement of the three primary inputs, the amount of wood/fuel consumed by each technology (By), the fraction of the woody biomass (or other type of fuel) that is non-renewable (*f*NRB) and the emission factors (EFs) of technologies, used to calculate the amount of emissions reductions all include varying levels of uncertainty (See Johnson et al., 2010).

The *f*NRB has particularly high levels of uncertainty involved in its calculation, which go unreported in accredited offsets (Johnson et al., 2010). GS provides more guidance about how to obtain this value, but both methodologies leave a lot of room for interpretation. As the *f*NRB determines the amount of wood saved that is eligible for CO_2 offsets, it has a large influence on the number of carbon credits calculated. The third primary variable, the EF of the baseline technology, is misrepresented by the CDM method using a default value based on a weighted fossil fuel mix (UNFCCC, 2011c). This default therefore does not reflect actual EFs involved in emission reduction cookstove projects. By contrast, the GS method uses either the EFs of the actual stoves involved in the project or the Intergovernmental Panel on Climate Change (IPCC) default EFs for both the baseline and project technologies (The Gold Standard, 2011b).

Though carbon credits represent relative climate impacts of each stove, neither methodology encompasses all climate forcings in their equations. Emissions of non-CO_2 climate-forcing species result in a positive emission rate contributing to climate warming even in the case of renewably harvested biomass (Smith et al., 2000b). Cookstoves emit three of the six GHGs included in the Kyoto protocol: CO_2, CH_4, and

N_2O (UNFCCC, 2011b; The Gold Standard, 2011b). In general, very little N_2O is emitted by cookstoves, so it is omitted from most calculations[8] (Smith et al., 2000b; Grieshop et al., 2011) and therefore is not included in this study's calculations. For cookstove projects, CDM only accounts for CO_2 (UNFCCC, 2011d) where the GS includes all three relevant Kyoto GHGs. However, cookstoves also emit climate-forcing species that are not included in the Kyoto Protocol. One challenge with including additional non-Kyoto climate-forcing species is the lack of agreement on Global Warming Potential (GWP) values assigned for them or, in some cases, even methods of measurement. In practice a number of climate-forcing species are left out of both methodologies: CO, NMHC, BC, OC and sulfur dioxide (SO_2).

BC is commonly known as soot and emitted in particulate matter. Although it is considered a 'short-lived particle' persisting in the atmosphere from a period of days to weeks it has a very high GWP and therefore can have significant short-term climate impacts (Bond and Sun, 2005; Kandlikar et al., 2009). Due to its very high GWP, there has been increased support to focus on BC as one mitigation piece to curb global warming (Bond and Sun, 2005; Grieshop et al., 2009; Jacobson, 2002; Kandlikar et al., 2009; Ramanathan and Carmichael, 2008; Reynolds and Kandlikar, 2008). Globally, household fires and cookstoves have been identified as one of the main emitters of BC due to the inefficient combustion of fuels. Advocates of BC mitigation stress the additional resulting health benefits as particulate matter is simultaneously reduced with BC through the use of more completely combusting

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[8] With the exception of coal-fueled stoves in some cases. Still, in this study, N_2O is not included for any of the scenarios.

stoves (Grieshop et al., 2009; Jacobson, 2002; Kandlikar et al., 2009). Due to BC's high GWP, including it in carbon credit calculations could markedly increase the amount of carbon credits received from clean cookstove projects. Including OC and SO_2[9] are also important as they have negative GWPs, contributing to climate cooling, may also have negative health impacts, and are co-emitted with BC (Smith et al., 2009; Grieshop et al. 2009).

2.6 Measuring Health Benefits

There are many health benefits associated with cookstove projects, the effects of which are mostly experienced by women and children (Rehfuess, 2006). The most cited health effects of IAP, which also have the strongest scientific support, are chronic obstructive pulmonary disease (COPD), acute lower respiratory infections (ALRI) and lung cancer (Rehfuess, 2006). Many studies use these more defendable health measures to evaluate the health implications of different kinds of cookstoves. Including only these three impacts of IAP, the emissions of concentrated smoke from the use of inefficient cookstoves are estimated to cause 1.6 million pre-mature deaths annually (Rehfuess, 2006).

The IAP from solid fuel burning is the result of PICs created through inefficient combustion of fuel. The extent of the health impact will largely be dependent on the individual inhalation of particulate matter emitted as part of PICs. Cookstoves with a venting system, such as a chimney, can help to greatly reduce this intake fraction

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[9] The emission of SO_2 is only relevant for coal and kerosene fueled stoves as biomass, charcoal and LPG fueled stoves have low or no emission of SO_2.

(Mehta and Shahpar, 2004; Smith et al., 2009b), but these emissions may still contribute to ambient air pollution, which could have negative health implications in some scenarios, particularly if in a densely populated location (Zhou et al., 2011; Wilkinson et al., 2009).

Other health impacts related to cookstove use include fatigue, physical strain, and/or injury while cooking and/or collecting fuelwood (Parikh, 2011). Additional dangers associated with collection of fuelwood are increased vulnerability to sexual violence for woman and young girls (Patrick, 2007), and injury from animals and other natural hazards (Holdren and Smith, 2000; Wickramasinghe, 2003; Matinga, 2008).

Although there are other associated development benefits beyond decreasing the impacts of IAP, health provides a good comparable measure to evaluate tradeoffs between climate and development benefits in carbon credit cookstove programs. Health impacts are far reaching and can be estimated based upon ambient concentrations of stove emissions similar to climate benefits estimated by direct stove emissions. Individual exposure to particulate matter can directly be translated into relative risk for different diseases associated with IAP. To evaluate health impacts of different stoves measures of individual exposure to $PM_{2.5}$ and relative risk are employed. Individual exposure provides a linear measure of potential relative health benefits of each different technology, where relative risk, translates these exposure values to represent the potential pattern that disease linked to IAP could follow. Both measures are based on exposure to $PM_{2.5,}$ as $PM_{2.5}$ is a common measure to quantify overall health impacts of IAP (Sinton et al., 2004; Naeher et al., 2007; Grieshop et al., 2011).

2.7 Comparing Climate and Health Benefits

A study by Grieshop et al. (2011) shows that health and climate benefits do not have a linear relationship for all cookstove types. Instead, some improved stoves generated higher climate benefits (the reduction of GHGs and other climate-forcing agents) while others generated higher health benefits (in this case relative risk of cardiopulmonary and cardiovascular disease mortality based on emissions of $PM_{2.5}$). For example, the unvented charcoal stove included in the analysis performed better than most of the biomass stoves in reducing relative health risk, but was one of the top emitters of GHGs[10]. The stoves with the highest 'win-win' benefits, having both low emission of GHGs and $PM_{2.5}$, were the liquid fossil fuel stoves[11] included in the analysis, the kerosene and liquid petroleum gas (LPG) stoves. Another study by Mehta and Shahpar (2004), also find fossil fuels stoves to have the highest health benefits in comparison with other improved biomass stoves, but note that kerosene creates slightly more IAP than LPG. Additionally they state kerosene has other health dangers associated with its use, such as poisoning and carcinogenic effects, making LPG the best overall stove for achieving health benefits.

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[10] Due to the large amount of GHGs emissions involved in charcoal production the analysis included charcoal production in the total amount of GHG emissions.

[11] When fossil fuels are referenced from here on they refer to the clean burning 'modern' liquid fossil fuels, specifically in this case kerosene and/or liquid petroleum gas (LPG), excluding coal unless otherwise noted.

Though Grieshop et al. (2011), provides the most comprehensive demonstration of climate and health tradeoffs in cookstove projects, other studies also have found tradeoffs in other cookstove scenarios. In a review of China's national cookstove program, Sinton et al. (2004) found that although the program was seen as one of the largest successes of cookstove distribution on a large scale, health benefits were not always automatically generated along with the targeted environmental benefits included in the program's objectives. This demonstrates an unintentional tradeoff made between climate and health benefits for a project who's main objective was to reduce pressures on biomass resources. Another study by Bailis et al. (2005) specifically examined climate and health tradeoffs between charcoal and fossil fuel stoves. They found that although both have relatively high health benefits, charcoal stoves have high negative climate impacts from the emission of GHGs both during production and the burning of fuel. Again fossil fuel stoves performed the best for both climate and health outcomes.

In the case of carbon credits the CDM does not accept projects switching to non-renewable fuels unless it is from high to low-carbon intensive fossil fuels (e.g. coal to LPG). Therefore the majority of scenarios with woody biomass as the baseline would not be eligible to switch to fossil fuel stoves under this framework (UNFCCC, 2011d). Comparatively the GS VER methodology allows projects switching to any kind of stove to be accredited as long as there are in fact emission reductions and the project meets all other methodological criteria. Therefore, if cookstove programs shift to become motivated by the carbon credit programs and policies are static, under market forces, stoves eligible for carbon credit certification with the highest GHG reduction will dominate and may create tradeoffs between the maximization of climate vs health benefits.

2.8 Additional Tradeoffs in Actual Project Implementation

Economic rationale has been provided for the implementation of cookstove projects and programs based upon the low relative cost of cookstoves compared to the large number of benefits they can create (Mehta and Shahpar, 2004; Bailis et al., 2005; Bruce et al., 2006; Hutton et al., 2006). Still effective cookstove dissemination has faced many challenges including making user-appropriate technology, providing affordable stoves for the targeted population, and developing effective business models for diffusion of improved cookstove technology (Hanbar and Karve, 2002; Rehman and Malhotra, 2004; Bailis et al., 2009; Troncoso, 2011; Shrimali et al., 2011).

Given that a large portion of the population that could most benefit from improved cooking technologies is comprised of financially poor families, in many cases cookstove dissemination needs to be subsidized (Bailis et al., 2009; Troncoso, 2011; Zerriffi ,2011). Currently there are a number of different national and international for-profit cookstove businesses (e.g. EcoZoom (EcoZoom, 2012), Biolite (Biolite, 2012), Philips (HHEN, 2010; Philips, 2011), Envirofit (Envirofit, 2011), First Energy (PCIA, 2011a; First Energy, 2012)). Most have had some form of international financial or in-kind support during their business development, are relatively young, and have yet to demonstrate a long-term sustainable business model (Shrimali et al., 2011). Businesses are limited to targeting consumer demographics that can afford to buy a stove, whereas donor-funded projects are limited in scale by the amount and frequency of funding. The opportunity to earn carbon credits has the potential to be a financial mechanism that can support cookstove projects on a much larger scale and target lower income demographics while still being a financially sustainable business model.

The success of such projects will be dependent on how the projects are designed (e.g. the type of stove, the cost of the stove vs revenue from carbon credits, strength of local partnerships, etc) and the extent to which projects integrate lessons learned from past cookstove intervention failures. These include, but are not limited to: accounting for user-preferences in stove design (Barnes et al., 1993; Rai and McDonald, 2009), having a reliable supply chain established if switching to a different fuel (Rai and McDonald, 2009; Wickramasinghe, 2011), availability of replacement parts/stoves and maintenance resources (Rai and McDonald, 2009), and user buy-in (Barnes et al., 1993; Rai and McDonald, 2009; Shrimali et al., 2011). Outcomes of cookstove carbon credit projects will also largely be influenced by how success is defined (e.g. highest number of carbon credits generated or stoves distributed, women empowerment, or improving health), and by whom. If equity is of concern in such projects, then market approaches alone will not suffice to deliver improved cooking technology to the poorest of the poor (Simon et al., 2012).

Different implementing actors have different motivations for engaging in stove projects, which are inherently integrated in their implementation design (e.g. profit seeking market-based approaches) or indicated in their mandate (e.g. an environmental NGO vs poverty-alleviation NGO). Similarly they have different sources of funding, whether this is mostly donor, national, or investment funding which places limits on the scale of projects they can complete. These two factors combined with the target demographic of cookstove users in cookstove projects, greatly determine the financial capacity, scale, and design of such projects and the metrics used to measure success.

2.9 Knowledge Gap

There have been some studies comparing the sustainable development outcomes between GS and CDM (Nussbaumer, 2009; Drupp, 2011) and motivations for using higher standard certification methodologies such as GS (Boyd and Salzman, 2011) for all project types, but there is limited literature comparing the CDM and GS methodology specifically for cookstove carbon credit projects. One study looks at the scientific robustness of GS and CDM methodological equations to calculate carbon credits for cookstove programs (Johnson et al., 2010), but there have been no studies in the peer-reviewed literature that have compared the amount of carbon credits that are calculated using each methodology in different scenarios**.** Simon et al. (2012) examines tradeoffs between 'win-win' benefits of carbon credit cookstove projects, but do not examine the tradeoffs directly between health and climate, mentioning only that health benefits are incrementally created along with climate benefits without accounting for the tradeoffs in levels of each benefit achieved. Specific tradeoffs between climate and health benefits of cookstove projects have been examined by Grieshop et al. (2011), in which comparisons were made between eleven stoves. However, Grieshop et al. (2011) do not use carbon credits as a measure of climate benefits and instead base their comparisons on actual stove emissions. The global warming commitments calculated per stove in their study do not compare emission reductions between stove switches and they do not base calculations on the carbon credit methodologies; therefore Grieshop et al. (2011) cannot account for how tradeoffs might be made in the actual market for carbon credits.

The analyses in this study focus on three areas. First, the two different methodological approaches for calculating carbon credits currently available through the CDM and the GS and the number of carbon credits calculated under each are compared. Second, some methodological specifics are examined. Current climate-forcing interactions included in the two methods, CDM and GS, are compared to other calculations with a more complete inventory of climate-forcing species and impacts of the *f*NRB variable on the amount of carbon credits calculated are explored through a sensitivity analysis. Lastly, tradeoffs between the amounts of climate and health benefits created in different scenarios are examined using the number of carbon credits calculated, and the estimated individual exposure to $PM_{2.5}$ and relative risk of potential disease mortality as measures of climate and health benefits.

3 METHODS

3.1 Overview

Drawing on work by Grieshop et al. (2011) discussed above, this study compares tradeoffs between climate and health, employing the same stoves used in their analysis, and their methods for measuring health impacts. For climate benefits, instead of emulating their methods to calculate direct stove emission reductions the CDM and the GS methods were used to calculate carbon credits as a measure of climate impacts. Additional climate-forcing species that are included in Grieshop et al.'s (2011) "GWC-All" scenario were also employed in other carbon credit calculations in order to theoretically demonstrate the impact of a more complete accounting of climate-forcings. These calculations were made under the framework of the two carbon credit methodologies, though neither equation accounts for these additional species at this time.

In this section the various methods and values used for this study's analyses are described, which include: the different stoves and EF values included in the analyses, the methods for calculating health benefits and carbon credits under both methodologies, CDM and GS, the methods for including additional climate-forcing interactions in the carbon credit calculations, and finally how climate and health benefits in each different scenario are compared.

3.2 Stove Types

Eleven stoves are included in this study. These can be roughly grouped into six categories based on similarities in thermal efficiency, amount of fuel use and fuel type: traditional biomass stove (W-Trad-U), basic improved biomass stoves (W-Im-U, W-Im-V, W-Pat-V), gasifying biomass stoves (W-Gas-U, W-Fan-U), coal-fueled stoves (Coal-U, Coal-V), charcoal-fueled stove (Char-U) and the cleaner burning liquid fossil fuel stoves (Kero-U, LPG-U). There still may be a lot of variation in specific stoves not included in this study that fall into one of these categories, but generally speaking the stoves included here provide a rough representation of the categories of stoves listed above. In this study the stoves are referred to both individually and in these loosely defined groups. For all the analyses the baseline stove was assumed to be a traditional stove (W-Trad-U). Therefore all the calculations of emission reductions are when switching from the W-Trad-U to one of the other ten stoves outlined in *Table 2*.

Table 2 A list of the eleven stoves in this study, including details about the location the stove is used, a brief description of the stove itself, and thermal efficiency and amount of fuel used for each stove. Assumed energy densities per fuel type employed in the carbon credit calculations are also included.

Stove Code	Location	Description	Thermal Efficiency	Estimated Fuel Use (t/yr)[f,12]	Energy Densities (TJ/t)[f]
W-Tr-U	India[a]/Mexico[b]	Traditional 'three-stone' stove or hand built mud stove.	18%[a]	2.69	0.015 (wood)[a]
W-Im-U	India[a]	Unvented, free-standing metal wood stove.	23%[a]	2.07	0.015 (wood)[a]
W-Im-V	China[c]	Brick wood stove with a chimney.	24%[c]	2.02	0.015 (wood)[a]
W-Pat-V	Mexico[b]	Masoned wood stove with chimney.	24%[g]	2.06	0.015 (wood)[a]
W-Gas-U	India[d]	Unvented, free-standing, top-feed, gasifying wood stove.	32%[d,h]	1.53	0.015 (wood)[a]
W-Fan-U	Philip's Stove[d]	Unvented, free-standing, Philip's 'Fan' wood stove with battery powered fan.	40%[d,h]	1.21	0.015 (wood)[a]
Coal-U	China[c]	Unvented, metal coal stove.	14%[a]	1.87	0.027 (coal)[c]
Coal-V	China[c]	Metal coal stove with chimney.	17%[c]	1.54	0.027 (coal)[c]
Char-U	India[e]	Unvented, free-standing basic charcoal stove.	18%[c]	1.58	0.026 (charcoal)[a]
Ker-U	India[a]/China[c]	Unvented, free-standing kerosene wick stove.	50%[a]	0.34	0.043 (kerosene)[a]
LPG-U	India[a]/China[c]	Unvented, free-standing liquid petroleum gas stove.	54%[a]	0.30	0.046 (LPG)[a]

[a]Smith et al., 2000a; [b]Johnson et al., 2008; [c]Zhang et al., 2000; [d]MacCarty et al., 2008; [e]Bailis et al., 2003; [f]Values taken from Grieshop et al., 2011. Original sources of data cited where relevant.; [g]Berrueta et al., 2008; [h]Jetter and Kariher, 2009

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[12] Grieshop et al. (2011) estimated annual fuel use by dividing 'at-the-cookpot' annual energy consumption (assumed to be 7300 MJ/yr) by the product of thermal efficiency (MJ delivered to pot/MJ of chemical potential in the fuel) and fuel energy content (MJ chemical potential/kg). They used values from laboratory tests as these provided consistent, comparable measures, even though efficiencies during in-home cooking usually vary from lab results.

3.3 Emission Factors

All EF values were measured from water boiling tests (WBTs), a common measure to determine stove performance based upon heat transfer and combustion efficiency (For a description of WBTs see Jetter and Kariher, 2009). Though this does not provide representative measures of actual EFs during cooking in homes, it provides a consistent, measure to compare all the stoves against. In-home stoves likely have higher EFs than those reported through WBTs, especially for $PM_{2.5}$ (Johnson et al., 2008). For the W-Trad-U stove, in-home EFs not derived by WBTs in Johnson et al. (2008) and Roden et al. (2006) were higher than the WBT measurements included in this study. This was particularly true for the emission of particulate matter, suggesting negative health impacts of traditional stoves may be higher than estimated in this study.

The GS methodology includes production and transportation EFs of fuel in addition to direct fuel use where relevant. Production EFs were included in calculations for coal, charcoal, kerosene, and LPG fuels in the GS calculations, but EFs for transportation of fuel were omitted as these will be varied based on the specific location and context of each project.

Table 3 Emission factors used in this study's calculations for each different stove type in gC/kg unless otherwise noted.

Stove	CO_2	CO	CH_4	NMHC	OC	BC	SO_2 (g/kg)	$PM_{2.5}$ (g/kg)	Production[13]
W-Tr-U[a]	382.28 ± 13.77	20.67 ± 1.67	2.92 ± 0.68	3.65 ± 0.44	2.15 ± 0.59	1.10 ± 0.25	0.27 ± 0.30	2.78 ± 0.60	N/A
W-Im-U[b]	391.75 ± 38.82	27.50 ± 5.25	3.00 ± 1.02	8.61 ± 2.39	1.41 ± 0.53	0.53 ± 0.19	0.27 ± 0.30	3.00 ± 0.72	N/A
W-Im-V[c]	425.45 ± 12.76	10.11 ± 1.82	0.45 ± 0.13	0.09 ± 0.08	0.72 ± 0.23	0.27 ± 0.08	0.27 ± 0.30	1.54 ± 0.20	N/A
W-Pat-V[d]	370 ± 21.35	22.33 ± 4.86	2.70 ± 0.93	4.10 ± 1.67	2.03 ± 0.66	0.93 ± 0.45	0.27 ± 0.30	3.23 ± 1.16	N/A
W-Gas-U[e]	463.64*	18.38*	1.74*	2.87*	0.59*	0.28*	0.27 ± 0.30	1.10*	N/A
W-Fan-U[e]	463.64*	1.67*	0.21*	0.97*	0.10*	0.06*	0.27 ± 0.30	0.20*	N/A
Coal-U[f]	684.55*	30.30*	7.73*	1.61*	2.35 ± 1.95	3.08 ± 2.32	0.15*	5.43 ± 3.03	0.52*
Coal-V[f]	736.36 ± 66.27	40.93 ± 15.55	2.64 ± 3.01	0.87 ± 0.90	2.35 ± 1.95	3.08 ± 2.32	0.88 ± 1.33	5.43 ± 3.03	0.52*
Char-U[g]	621.82 ± 9.27	111.43 ± 4.29	13.50 ± 4.50	2.13 ± 0.60	0.25 ± 0.32	0.18 ± 0.23	0.40*	0.40 ± 0.50	524.90 ± 6.41
Ker-U[h]	838.20 ± 28.39	5.65 ± 1.21	0.12 ± 0.07	5.05 ± 0.64	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.03	0.26 ± 0.15	179.84*
LPG-U[h]	842.06 ± 22.28	3.69 ± 0.85	0.22 ± 0.35	7.35 ± 2.04	0.07 ± 0.06	0.07 ± 0.06	N/A	0.52 ± 0.45	96.78*

*No standard deviation values available in original studies.

[a] CO_2, CO, CH_4, NMHC (Johnson et al., 2008; Smith et al., 2000a); OC, EC, $PM_{2.5}$ (Johnson et al., 2008); SO_2 (Andreae and Merlet, 2001) [b]CO_2, CO, CH_4, NMHC (Smith et al., 2000a); OC, EC, $PM_{2.5}$ (Roden et al., 2006); SO_2 (Andreae and Merlet, 2001) [c]CO_2, CO, CH_4, NMHC (Zhang et al., 2000); OC, EC, $PM_{2.5}$ (Roden et al., 2006); SO_2 (Andreae and Merlet, 2001) [d]CO_2, CO, CH_4, NMHC, OC, EC, $PM_{2.5}$ (Johnson et al., 2008); SO_2 (Andreae and Merlet, 2001) [e]CO_2, CO, CH_4, NMHC, OC, EC, $PM_{2.5}$ (MacCarty et al., 2008); SO_2 (Andreae and Merlet, 2001) [f]CO_2, CO, CH_4, NMHC, SO_2, $PM_{2.5}$ (Zhang et al., 2000); OC and EC fractions (Bond et al., 2004); Production (IPCC, 1996) [g]CO_2, CO, CH_4, NMHC,

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[13] Emissions of CO_2, CH_4 and N_2O were included in the estimation of the production EF. As the EFs for production were not available for all of the climate forcers included in the *All Species* scenarios (See Section *3.7*), production EFs were not included in these calculations, only in the *Allowable Credits* scenarios (See Section *3.6*).

$PM_{2.5}$ (Bailis et al., 2003); OC and EC fractions (Bond et al., 2004); SO_2 (Andreae and Merlet, 2001); Production(Pennise et al., 2001) [h] CO_2, CO, CH_4, NMHC, $PM_{2.5}$ (Zhang et al., 2000; Smith et al., 2000a); OC and EC fractions (Bond et al., 2004); SO_2 (Value for Kero-U only, Zhang et al., 2000) ;Production (Defra, 2012)

3.4 Measuring Climate Impacts: Carbon Credits

For climate benefits, carbon credits of cookstove projects were calculated using both the CDM and GS methodologies. All emissions calculated are in tCO_2e, where one tCO_2e equals one carbon credit. Carbon credits reported here represent amount of tCO_2e reduced per year per stove. For both equations CO_2 emitted from burning of renewable biomass is not included as it is assumed to be carbon neutral, with the amount of carbon emitted being re-sequestered through forest regeneration. This assumption is reflected through the inclusion of the *f*NRB variable in both equations. The equations for both methodologies are outlined below.

3.4.1 CDM

The CDM methodology used for calculating CER credits for cookstoves is called, "AMS-II.G Energy efficiency measures in thermal applications of non-renewable biomass" (UNFCCC, 2011d). There are four variables used to calculate emission reductions (**ER_y**) which is expressed in tCO_2e during the year y:

$$ER_y = B_{y,savings} * f_{NRB,y} * NCV * EF_{projected\ fossilfuel} \quad (\textbf{Equation C.1})$$

Where **$B_{y,savings}$** is the amount of fuel saved in tonnes through the project activities in year y, which here only the amount per stove is included, **$f_{NRB,y}$** is the fraction of non-renewable biomass saved in year y**, NCV** is the net calorific value of the woody biomass or other type of fuel, and **$EF_{projected\ fossilfuel}$** is the default emission factor, 81.6 tCO_2/TJ, representing the "substitution of non-renewable woody biomass by similar consumers" based on a mix of weighted fossil fuels. There are two important notes to be made regarding this use of a fossil-fuel EF. First, this factor is on an energy basis (tCO2/TJ) while the EFs presented in *Table 3* are on a mass basis (gC/kg fuel). Second, it represents the EF of the baseline stove in the project, usually a traditional stove. The equation still bases the amount of fuel saved on the actual baseline and project stoves' relative efficiencies and the amount fuel needed for meeting energy requirements, but utilizes a misrepresentative default fossil-fuel EF. This is meant to provide conservative estimates without requiring the actual measurement of the traditional stove EFs, but at the same time it does not reflect the actual specific emission reductions.

It is also important to note that the CDM does not allow fossil fuel based stoves (e.g. LPG) to obtain credits unless switching from a high to low carbon intensive fossil fuel (e.g. coal to LPG). Therefore, in the results reported below there are two numbers included for the LPG and kerosene stoves: zero for the actual credits possible under the CDM and a second value for the credits that would be generated using *Equation C.1* above, if switching from a traditional to fossil fuel stove was allowed.

3.4.2 GS

To calculate GS VER credits the GS methodology, "Technologies and Practices to Displace Decentralized Thermal Energy Consumption" was used (The Gold Standard, 2011b). For EFs GS allows the use of IPCC defaults for baseline and/or project emissions, if they cannot be measured directly in the project context. Overall GS's estimates are more representative of actual emission reductions even when using default EF values, than the CDM method as they calculate both baseline and project emissions. The equation used is as follows:

$$ER_y = \sum_{b,p} N_{p,y} * U_{p,y} * (f_{NRB,b,y} * ER_{b,p,y,\,CO2} + ER_{b,p,y,\,non\text{-}CO2}) - \sum LE_{p,y}$$ (**Equation G.1**)

Where $\sum_{b,p}$ is the sum of all the different baseline and project scenarios, $N_{p,y}$ is the number of 'technology-days' included in the project period in year y, here assumed to be 365 days, $U_{p,y}$ is the rate of usage of project technologies during year y as a fraction, here assumed to be 100%, $f_{NRB,b,y}$ is the fraction of non-renewable biomass for the baseline scenario in year y, $ER_{b,p,y,\,CO2}$ is the emission reductions of CO_2 when switching from the baseline to project technology in year y, measured in tCO_2 per day, $ER_{b,p,y,\,non\text{-}CO2}$ is the amount of emission reductions of non-CO_2 emissions, CH_4 and N_2O, when switching from the baseline to project technology in year y, in units of tCO2e per year, for which only CH_4 is included in this study's equations, and $LE_{p,y}$ is leakage for the project scenario in year y, in tCO2e per year, here assumed to be zero for all calculations.

3.5 CDM vs GS

The amount of carbon credits were calculated and compared when switching from the W-Trad-U stove to all other stoves included in the study under the two different methodologies, CDM and GS using *Equation C.1* and *Equation G.1*. These scenarios are referred to as '*Allowable Credits*'. For both these calculations the *f*NRB was assumed to be a value of 75%. After a review of the current registered cookstove projects both under CDM and GS, 75% was found to be at the lower end of the estimated reported values. Many projects include *f*NRB values up into the 90th percentile range. Therefore by applying this value in these calculations, the resulting carbon credits calculated are relatively conservative estimates. Additionally, approximately how much can be earned per scenario (which again measures number of carbon credits per stove per year) was calculated employing the prices found in *Table 1*. The average price per carbon credit was used for all project types under the CDM for the CER credits and the average price specifically for cookstove projects for the VER credits. This is only an approximation and actual prices and income may greatly vary from the ones provided here.

3.6 Accounting for Additional Climate Forcings

As neither methodology accounts for all climate forcers, climate impacts were calculated using the framework of both methodologies by including the following species: CO_2, CH_4, CO, NMHC, OC, BC and SO_2. These calculation scenarios are referred to as '*All Species*'. EF values found in *Table 3* were used, derived from previous studies for these calculations. Each specific species' EFs were employed in the CDM methodology instead of using the default EF value and the amount of carbon credits for each different species was calculated individually. For non-CO_2 gases the *f*NRB variable was omitted from the equation. The sum of all the individual species calculations equal the total carbon credits calculated for the *All Species* scenarios. GWP values for a 100-year period applied for each different species can be found in *Table 4*[14] . These *All Species* carbon credit values are then compared with the amount calculated in the *Allowable Credits* scenarios.

Table 4 GWP_{100} values for all species included in the study.

Species	**GWP_{100}**
Kyoto Gases	
CO_2	1[a]
CH_4	25[a]
Other Species	
CO	1.9[a]
NMHC	3.4[a]
BC	455[b]
OC	-35[b]
SO_2	-76[c]

[a]IPCC, 2007; [b]Reynolds and Kandlikar, 2008; [c]Shindell et al., 2009

3.7 *f*NRB Sensitivity Analysis

The methods to calculate the *f*NRB lack specificity in both methodologies though GS provides marginally more detailed guidelines than CDM. Under both approaches high levels of uncertainty through coarse estimates and inconsistent methodological approaches are incorporated into estimates of the *f*NRB. It is beyond the scope of this study to analyze the process in determining this value. Instead the variability that different values of *f*NRB can create is demonstrated. Using a sensitivity analysis carbon credits were calculated under both methodologies using *Equation C.1* and *Equation G.1,* for all stoves using values: 25%, 50%, 75%, 85% and 95%. The

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[14] The time frame for which the GWPs are defined by can greatly change the values calculated. This is particularly true for BC which is a very short-lived climate forcer. For example, one estimate of a GWP value for a 20-year period for BC is 2200 (Bond and Sun, 2005).

majority of reported values in actual projects are in the range of 75-100%. Including the values 25% and 50% demonstrate the potential variability in carbon credits calculated if the reported range was extended.

3.8 Estimating Health Impacts: Individual Exposure and Relative Risk

Two health effect estimates are employed in this study: reduction of individual exposure to $PM_{2.5}$ and relative risk of disease mortality. For both effect estimates, individual exposure to $PM_{2.5}$ in mg per day for each different kind of stove was first calculated based upon the $PM_{2.5}$ emissions per stove, the amount of fuel burned, and the exposure fraction an individual experiences (See *Equation H.1*). Reduced exposure to emissions due to a venting system such as a chimney or flue was also incorporated into the calculation.

To determine the first effect estimate of health, values of individual exposure to $PM_{2.5}$ were translated into relative risk of disease mortality using Pope et al. (2009)'s log-linear intake-response relationship (relative risk = $1+0.2968(\text{dose})^{0.2107}$) developed for cardiovascular disease (CVD) (See *Figure 5*). Pope et al. (2009)'s intake response curve for CVD is primarily based on empirical data from urban air pollution and second hand smoke at the lower end of the scale and primary cigarette smoking at the higher end of the scale. Typical doses from cookstoves are in between these two exposure ranges and it has also been proposed that two of the three main health impacts more strongly associated with IAP, COPD and ALRI, exhibit a similar non-linear relationship (Smith and Peel, 2010). There has not yet been any direct empirical evidence to support this theory, therefore the relative risk relationship presented here is only theoretical and includes high levels of uncertainty. Including relative risk demonstrates the additional complexity of health benefit estimations, as these are probably not incremental (with the exception of lung cancer, which most likely does follow a linear relationship (Smith and Peel, 2010)) and reflects a non-linear relationship, which the health impacts of IAP could likely follow.

The second health effect included in the analyses estimates the relative health benefit when switching from the baseline stove to the other ten stoves included in this study. These values were determined by calculating the difference between individual exposure values to determine the overall reduction in individual exposure to $PM_{2.5}$ (See *Table 5*). In comparison to the measure of relative risk, the measure in the difference of individual exposure reflects a linear relationship. As its values are based more directly on stove performance and emissions, these values incorporate less uncertainty, but are limited in the representation of actual impact on health conditions. It better reflects the relative performance of each stove's potential health benefits, but not actual potential health impacts.

Both health effects provide an estimate of health per individual, a unit easily comparable to carbon credits, which are incrementally calculated per stove. Yet, these values only provide an approximate measure of health impacts per stove as they have different levels of uncertainty associated with their values and actual impacts in such projects may vary greatly due to a number of variables impacting outcomes. Still they are effective relative measures by which to compare performance between the individual stoves and corresponding carbon credits.

Individual Exposure = $AFU*EF_{PM2.5}*iFi*f_{unv}*1/365$ (**Equation H.1**)

This equation is derived from an individual intake fraction equation from Bennett et al. (2002) linking mass emitted and mass inhaled. Here individual intake is instead referred to as individual exposure as it better describes what the calculated values represent. Individual exposure is measured in mg per day where **AFU** is the annual fuel use measured in kg fuel per year, **$EF_{PM2.5}$** is the emission factor of $PM_{2.5}$, **iFi** is the individual exposure fraction measured in mg exposed per mg emitted here assumed to be 1300*10^-6 mg per mg based upon a median of the most exposed and highest risk group, females from 16-50 years of age (Grieshop et al., 2011), and **f_{unv}** is the fraction of emissions not vented via a chimney. When there is no chimney present f_{unv} is assumed to be 1. For the vented stoves included in this study, a value of 0.18 is used, which was derived by Grieshop et al. (2011) from a conglomerate of studies. The equation is lastly multiplied by 1/365 to get a measurement per day not per year, a standard unit of measure of health impacts in this area of study.

3.9 Comparing Health and Climate Benefits

With the amount of carbon credits resulting from both the *Allowable Credits* and *All Species* calculations, the scenarios were ranked from those creating the most carbon credits to the least. Similarly the different stoves were also ranked to represent health benefits based upon the reduction of individual exposure to $PM_{2.5}$ from the highest reduction to the least and for relative risk from the least to the most risk.

Finally the rankings of climate and health benefits for each stove were compared under both CDM and GS methodologies for *Allowable Credits* and *All Species* scenarios.

4 RESULTS

4.1 CDM vs GS: Carbon Credits Calculated

Figure 1 compares GS and CDM methodologies for all *Allowable Credit*s scenarios. In all cases except for Coal-U and Char-U, where both have 'negative' carbon credits (i.e. GHG emissions increase rather than decrease), GS out-performs CDM in the number of credits calculated. When including EFs for production of processed or extracted fuels, the LPG-U stove creates the most carbon credits under the GS methodology, closely followed by the Kero-U. Under GS the next best performing stove for climate is the W-Fan-U stove, but it calculates more than 0.5 of a credit less than kerosene. Under the CDM methodology, the W-Fan-U stove performs the best as the CDM does not credit projects switching from biomass to fossil fuel stoves. If they did include such stoves in their methodology, Kero-U and LPG-U would generate the highest amount of carbon credits out of the CDM scenarios included in the analysis, but with W-Fan-U closer in comparison to these two fossil fuel stoves than under GS. The income generated per scenario varied; neither methodology calculated a higher income per stove in all scenarios.

For the biomass stoves, the Fan-U and Gas-U, the more technologically advanced models, out-performed the other stoves. When comparing the basic models of biomass stoves (W-Im-U, W-Im-V, W-Pat-V) along with the coal stoves, the vented stoves performed better under GS, with the W-Pat-V generating the most amount of carbon credits. There wasn't much of a difference between the basic biomass stoves under the CDM methodology. For the Coal-U, Coal-V and Char-U stoves, these had values of close to zero, zero, or negative emissions reductions under both methodologies.

If just comparing the emission reductions of CO_2 calculated under each methodology there is much more variation as to which methodology exceeds the other in each different scenario.

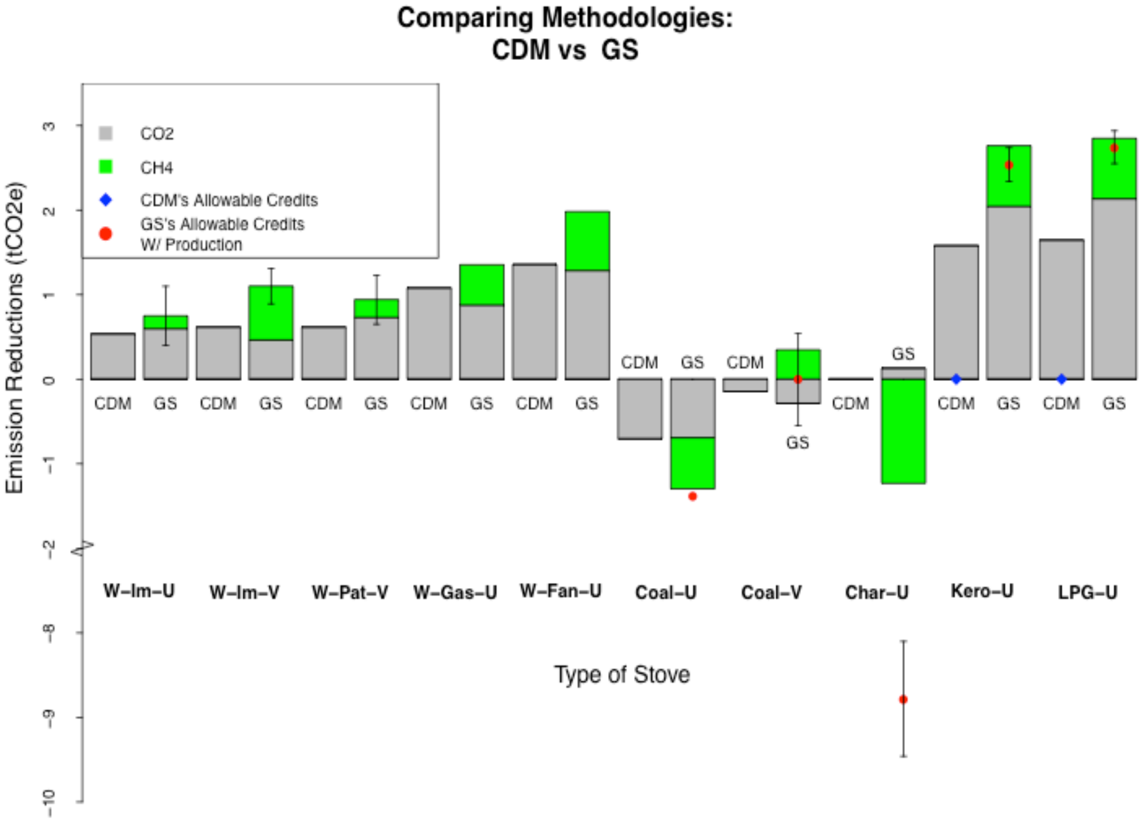

Figure 1 Comparing CDM and GS methodologies for the number of carbon credit calculated. All scenarios are switching from the W-Trad-U stove to one of the ten improved stoves using a 75% value for the *f*NRB. As GS can include EFs associated with the production of processed or extracted fuels, the production EFs for Coal-U, Coal-V, Char-U, Kero-U and LPG-U are included in these GS calculations, indicated by the red dots. The Char-U stove has particularly high emissions associated with its production resulting in the extra negative amount of carbon credits calculated. As CDM uses a default EF, there are no confidence bounds for any of the CDM calculations. For GS, standard deviation was not available in the original studies for W-Gas-U, W-Fan-U or Coal-U and therefore these stove scenarios do not include the confidence bounds. As CDM does not accept cookstove projects that switch to a fossil fuel stove from a traditional stove, the real values for Kero-U and LPG-U would be zero (blue diamonds), but a theoretical calculation applying the CDM equation to these stoves was included as a comparison to GS.

4.1.1 Accounting for Additional Climate Forcings

Figure 2 displays the impact of including different climate-forcing species using both carbon credit methodologies. The inclusion of BC has the most significant impact on the amount of carbon credits calculated as it increases the values in all the scenarios with the exception of Coal-U and Coal-V, even when including OC and SO_2, climate cooling species. An EF for fuel production was not included in any of these calculations as values could not be obtained for all species. Therefore carbon credit estimates for the coal, charcoal and fossil fuel stoves under the GS methodology are overestimated. The top three performing stoves under both methodologies are again the W-Fan-U biomass stove and the two fossil fuel stoves, Kero-U and LPG-U. The other biomass stoves perform differently under the two different methodologies. The W-Gas-U stove does relatively well under both CDM and GS whereas W-Im-U, W-Im-V, and W-Pat-V have approximately the same number of carbon credits under the CDM and are much more varied under the GS. In these scenarios, GS still calculates more carbon credits than the CDM, even when the CDM methodology employs actual EFs and does not use the default EF value.

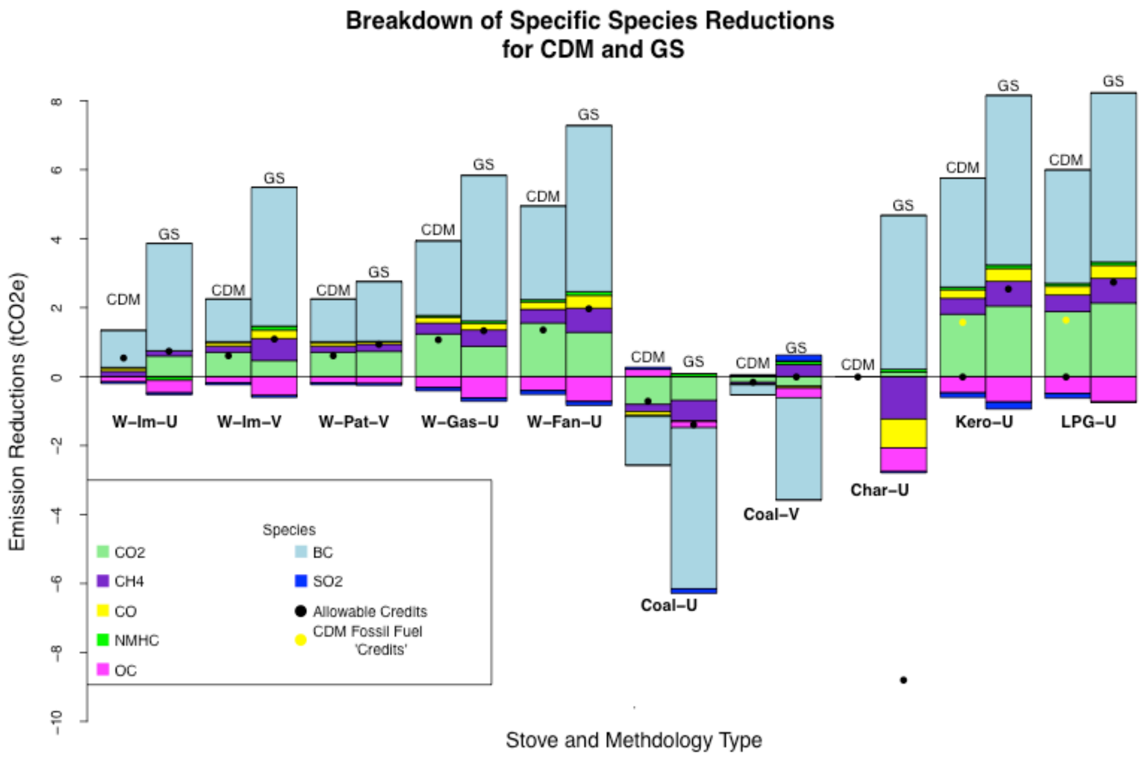

Figure 2 Breakdown of the different climate-forcing species included in the *All Species* analysis for each different stove under each different methodology when switching from the W-Trad-U stove to each respective project technology. For all calculations a 75% value for the *f*NRB was used. Values of *Allowable Credits* under normal CDM and GS methodologies are indicated by the black dots. Since CDM does not certify projects that switch to fossil fuels from a traditional, biomass stove, their hypothetical normal values are indicated by the yellow dots. For *All Species* calculated under the CDM methodology actual EF values were used instead of the default EF. Emissions from production of fuels were not included in the individual species emissions calculations. Therefore the carbon credits calculated in these *All Species* scenarios may be overestimated for: Coal-U, Coal-V, Char-U, Kero-U and LPG-U.

4.1.2 Fraction of Non-Renewable Biomass

Figure 3 compares the different stove scenarios under CDM and GS when using different values of the *f*NRB in the calculations. In general the higher the value of the *f*NRB the higher the amount of carbon credits per year per stove calculated under both methodologies with the exception of Coal-U, Coal-V and Char-U, in which the inverse relationship is true (exception: Char-U under CDM, where it equaled zero when using all different values of the *f*NRB). For the other seven stoves the difference of carbon credits calculated when using 25% and 95% values of *f*NRB ranged from 0.44 to 1.99 carbon credits with an average difference of 0.68 carbon credits under the GS and 0.62 carbon credits under the CDM. For the *f*NRB values of 75% and 95% the difference in the number of credits calculated for the seven stoves ranged from 0.13 to 0.57 with an average difference of 0.18 for CDM and 0.20 for GS. For the fossil fuel stoves the differing values of the *f*NRB have an especially large impact on the number of carbon credits calculated with high values of the *f*NRB greatly increasing the number of carbon credits calculated.

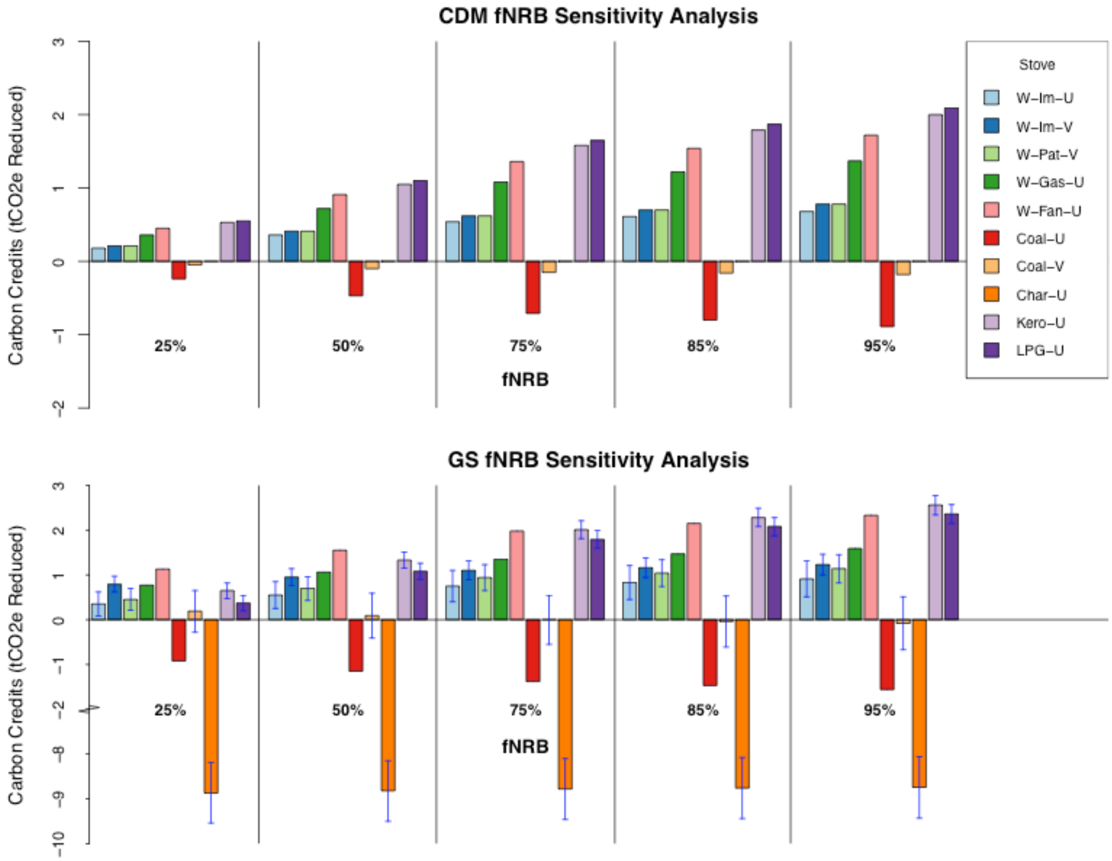

Figure 3 Sensitivity analyses for the fraction of non-renewable biomass under both the CDM and GS using values of 25%, 50%, 75%, 85% and 95%. Note the difference in scale as the GS values span a much larger range of values than the CDM. Since CDM calculations employ a default EF there is no uncertainty represented for any of these values. For the GS calculations, values of standard deviation

were not available for the EFs of the W-Gas-U, W-Fan-U and Coal-U stoves and therefore uncertainty is not represented for these stoves either.

4.2 Health Performance

Table 5 lists estimated health performance for the stoves included in the study. The stoves are ranked from top performing (having the least relative risk and greatest reduction in individual exposure) to the worst (with the most relative risk and least reduction in individual exposure). All stoves besides the Coal-U stove have a lower relative risk than the W-Trad-U stove. *Figure* 5 visually demonstrates the estimated relationship between relative risk and individual exposure for each stove. This non-linear dose-response relationship shows reductions in exposure at already low levels of exposure will have the greatest impact in reducing the amount of relative risk. This is only a rough estimation of health impacts based on Smith and Peel (2010)'s interpolation of Pope et al. (2009)'s CVD dose response curve. However, there is no direct empirical evidence as of yet for the relationship between $PM_{2.5}$ from household combustion and CVD.[15] Based on this theoretical work, Smith and Peel (2010) show that to achieve the highest levels of positive health impacts and to achieve the highest reduction in relative risk, individual intake of $PM_{2.5}$ needs to be less than 1 mg/day. In this analysis only the top three performing stoves meet these levels, the Kero-U, LPG-U and W-Fan-U stoves (corresponding to a relative risk of less than 1.3), but again currently this is only a theoretical threshold. Regardless, the

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[15] The best evidence for health effects of household smoke are its impacts on respiratory diseases such as COPD and ALRI. Smith and Peel propose that these also follow a similar non-linear function. The relative risks calculated here are not for those diseases, as a dose-response curve has not been developed for them as of yet.

two effect estimates of health demonstrated here, both the linear individual exposure and non-linear relative risk, can be used as relative estimates to compare the health performance between stoves.

4.3 Climate vs Health

The top three stoves for both climate and health in all scenarios, with the exception of CDM's *Allowable Credits* (where fossil fuel stoves are excluded), are Kero-U, LPG-U and W-Fan-U (See *Figure 4* and *Table 5*). Climate benefits are maximized in the *All Species* scenarios, but the actual pattern of ranked climate benefits depends on the type of stove, methodology and scenario (See *Figure 6*). For health, with the exception of the high performing W-Fan-U stove, the vented stoves performed better in the analysis than non-vented stoves when comparing the biomass or coal stoves. Charcoal performs well for individual exposure as it burns relatively cleanly (See *Table 5* and *Figure 5*) and has a low relative risk value. Yet the climate emissions of charcoal during the production phase are so high, this results in zero or negative values of carbon credits. The W-Gas-U stove is the 4th top-performing stove for climate benefits in all the scenarios, yet it is the 3rd worst stove for health benefits. Still its health benefits far exceed those of the two worst performing stoves as the W-Gas-U associated individual exposure value is less than 10 mg/day, situating it in Smith and Peel (2008)'s second best tier for health measures. The coal stoves perform especially poorly for both climate and health benefits, but including a chimney can significantly improve health performance measures.

Table 5 Ranking different scenarios for climate and health benefits. The climate scenarios are ranked based on the number of carbon credits calculated. A potential income for each scenario is also included using 2011 average carbon prices for cookstove projects for GS ($13) and all projects for CDM ($17.38) (See *Table 1*). The *All Species* climate scenario is theoretical and includes all the climate-forcing species included in *Figure 2*: CO_2, CH_4, CO, NMHC, OC, BC and SO_2.

Climate: Allowable Credits Carbon Credits (tCO_2e/year) and Potential Income ($)						**Climate: All Species** Carbon Credits (tCO_2e/year) and Potential Income ($)						**Health**		
GS			**CDM**			**GS**			**CDM**				Reduction of Individual Exposure to $PM_{2.5}$ (mg/day)	Relative Risk
LPG-U	2.74	$35.62	**LPG-U**	1.65[*]	$28.68	**LPG-U**	7.49	$97.37	**LPG-U**	5.37	$93.23	**Kero-U**	26.34	1.23
Kero-U	2.54	$33.02	**Kero-U**	1.58[*]	$27.46	**Kero-U**	7.21	$93.73	**Kero-U**	5.15	$89.51	**LPG-U**	26.11	1.26
W-Fan-U	1.98	$25.74	**W-Fan-U**	1.36	$23.64	**W-Fan-U**	6.44	$83.72	**W-Fan-U**	4.43	$76.99	**W-Fan-U**	25.80	1.29
W-Gas-U	1.35	$17.55	**W-Gas-U**	1.08	$18.77	**W-Im-V**	5.12	$66.56	**W-Gas-U**	3.52	$61.18	**W-Im-V**	24.67	1.34
W-Im-V	1.10	$14.30	**W-Im-V**	0.62	$10.78	**W-Gas-U**	4.88	$63.44	**W-Im-V**	2.01	$34.93	**Char-U**	24.41	1.35
W-Pat-V	0.94	$12.22	**W-Pat-V**	0.62	$10.78	**W-Im-U**	3.34	$43.42	**W-Pat-V**	2.01	$34.93	**W-Pat-V**	22.39	1.40
W-Im-U	0.75	$9.75	**W-Im-U**	0.54	$9.39	**W-Pat-V**	2.40	$31.20	**W-Im-U**	1.75	$30.42	**Coal-V**	21.30	1.42
Coal-V	0.00	$0	**Char-U**	0.00	$0	**Char-U**	1.89	$24.57	**Char-U**	0.00	$0	**W-Gas-U**	20.67	1.43
Coal-U	-1.38	$0	**Coal-V**	-0.15	$0	**Coal-V**	-2.95	$0	**Coal-V**	-0.47	$0	**W-Im-U**	4.56	1.57[x]
Char-U	-8.78	$0	**Coal-U**	-0.71	$0	**Coal-U**	-6.19	$0	**Coal-U**	-2.30	$0	**Coal-U**	-9.50	1.63[x]

[*] Scenarios not possible under current CDM methodological framework.

[x] The relative risk of W-Trad-U is: 1.59, which falls between W-Im-U and Coal-U

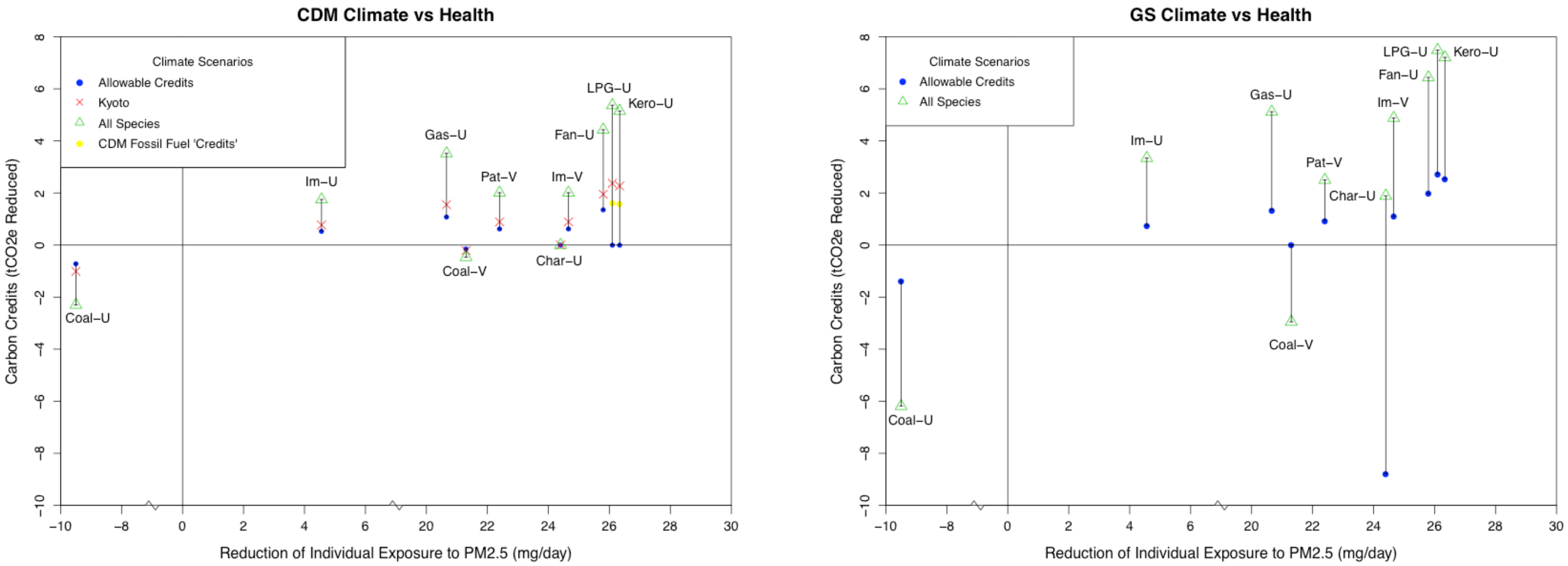

Figure 4 Comparing measures of climate benefits in the form of carbon credits calculated and health benefits in the form of reduction of individual exposure to $PM_{2.5}$ under both methodologies, CDM and GS. In each comparison *Allowable Credits* and *All Species* scenarios are included. For the CDM a 'Kyoto' scenario is also included, which calculates emission reduction of both CO_2 and CH_4. As GS methodology already includes both these species in its *Allowable Credits* scenario, this in not included for GS. Since LPG and kerosene fueled stoves are not eligible for CDM credits when switching from a biomass stove, the yellow circles represent the theoretical credits that could be received under normal calculations if these stoves were eligible for credits. Note the two breaks in the x-axis.

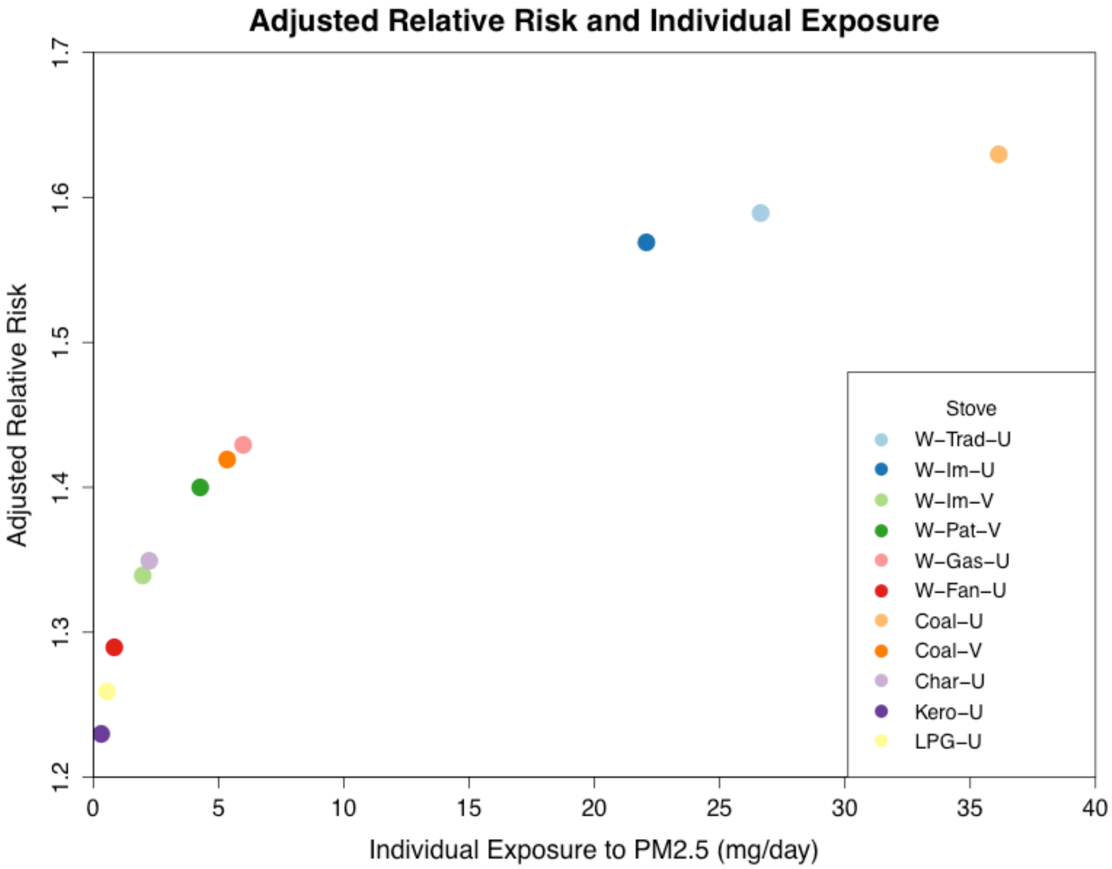

Figure 5 Adjusted relative risk vs individual exposure of $PM_{2.5}$ in mg/day. Relative risk is assumed to be equal to: $1+0.2968(dose)^{0.2107}$, derived from Pope et al. (2009), where the dose is individual exposure to $PM_{2.5}$. The only stove to perform worse than the W-Trad-U is Coal-U. In all other scenarios a switch from the W-Trad-U stove to another stove provides some level of health improvement.

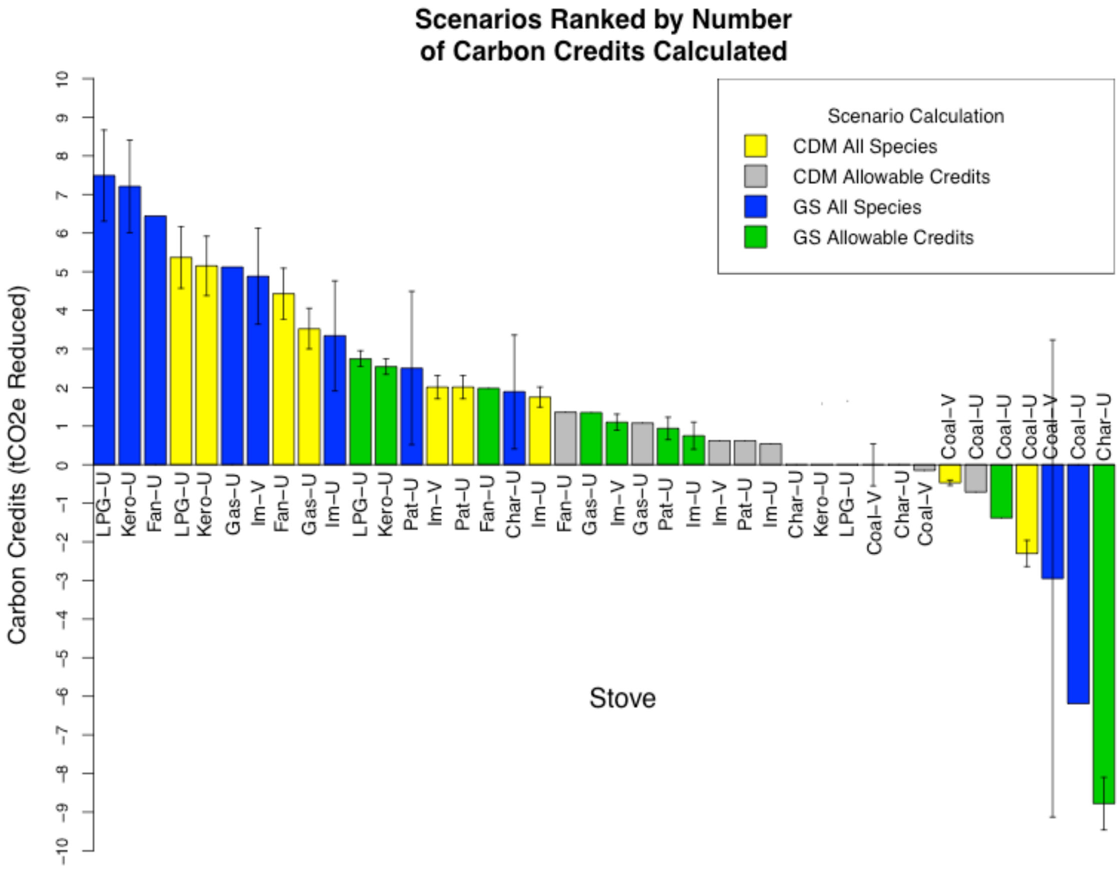

Figure 6 Scenarios based on the type of stove, methodology and scenario ranked for the amount of carbon credits calculated from most to least. In general *All Species* scenarios perform better than *Allowable Credits* and GS better than CDM. The scenarios in the top quartile include the LPG-U, Kero-U, Fan-U, Gas-U, Im-V and Im-U stoves. The scenarios in the bottom quartile include the Char-U, Coal-U, and Coal-V stoves.

5 DISCUSSION

5.1 Choosing a Methodology

One salient finding of this research is the difference in carbon credits calculated between the two methodologies. In almost all scenarios the carbon credits under the GS methodology exceeds those calculated by CDM (up to 1.79 times under the *Allowable Credit* scenarios). The inclusion of CH_4 in GS calculations largely accounts for this discrepancy. For CO_2 reductions only, neither methodology is dominant across all stoves[16]. When comparing theoretical prices per stove scenario, on the outset it would seem CDM would earn more per stove offset due to the higher average price per credit. Yet, as GS calculated more credits per stove than CDM in most scenarios and cookstoves projects specifically earned more than the average project in the voluntary market, there is more variation, without one methodology consistently having a higher theoretical price per stove. As the state of carbon markets continue to be uncertain these relationships could drastically change. In addition, there is no data specifically for cookstove project CERs, which could mean that cookstove credits under the CDM could potentially have even higher prices.

Overall, the GS methodology more accurately represents actual emission reductions as it bases these on the difference between the project and baseline stoves rather than a default EF based equation. Still, the choice to use CDM or GS will probably be most dependent upon whether or not the project developer wants to apply for CER

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[16] Note, these values are highly dependent on the poorly defined *f*NRB estimation. Therefore this relationship will vary depending on the values of *f*NRB employed.

or VER credits. There are many considerations made in this decision, such as the cost of becoming certified, the size of the project, the types of credits potential investors are interested in and the price earned per credit. No previous studies were found to have compared the difference in calculable credits between the two methodologies. Therefore this research presents another consideration to be included when making such decisions, the effect of which will likely be directly dependent on the prices of credits in both carbon markets.

5.2 Methodological Game Changers

5.2.1 Black Carbon

The inclusion of BC in both methodological calculations would greatly increase the number of carbon credits certified for cookstove projects. This is the case even when including both OC and SO_2, two cooling species that are co-emitted with BC. These additional credits could considerably enhance the profitability of such projects, the largest positive change in the scenarios in this study resulting in more than a 4-fold increase in the number of carbon credits. There has been some discussion regarding allowing credits for BC (PCIA, 2011b), but there has not been any serious momentum to push this idea forward. One of the challenges for integrating BC into such calculations is that there is no agreed upon GWP value and estimates of this can vary widely with higher levels of uncertainty as it is much more variable than longer lived climate forcers such as CO_2. As BC climate impacts are created during a very short time period, the use of different GWP time frames will greatly influence how the impact of BC is perceived. Therefore representing the impacts of BC with GWP is not ideal, but is the current standard widely used for understanding climate-forcing impacts. Additionally the impacts of BC can be very different depending on the regional location. As its warming effect is due to the absorption of sunlight through decreased albedo, if these particles land on a black surface, such as pavement, the warming impact will be very different than when landing on a white surface, such as a glacier; the prior having minimal or no warming impact with the latter greatly increasing the climate forcing effect. This presents a challenge to represent actual climate impacts without making the methodologies by which to determine them prohibitively complex. As approximately 60% of global BC emissions are from contained combustion (Bond et al., 2004), incentivizing the reduction of BC through cookstove projects has the potential to significantly mitigate climate warming relevant emissions. In addition, the emission of BC, unlike CO_2 and CH_4, is directly related to the emissions of $PM_{2.5}$. However, in this analysis the inclusion of BC does not reflect the same pattern of health benefits for all stove scenarios (See *Table 5*). Therefore simply including BC will not account for all health considerations even though it does significantly account for additional climate impacts not currently included in either methodology. More research into the relationship between BC and climate and health benefits of cookstoves could help to further clarify these interactions.

5.2.2 fNRB

The *f*NRB is another variable that can greatly influence the amount of carbon credits calculated. This value attempts to prevent carbon leakage by only crediting CO_2 emissions reduced from the reduction of non-renewable biomass fuel sources. Its inclusion requires projects to be in areas with some level of non-renewable fuel extraction to qualify for carbon credits. As the *f*NRB determines the amount of reduced fuel that can be used to calculate CO_2 emission reductions, the amount of carbon credits calculated are highly sensitive to this value. The large difference between calculations utilizing *f*NRB values of 25% and 95% demonstrates the substantial variability included in calculations. This can significantly change the amount of carbon credits calculated especially when applying the differences per individual stove to an entire project for example with 10,000 or 21,500 stoves. In the range of values most commonly reported in actual projects, 75%-95%, the variability is reduced. Still the scenario with the largest difference, GS LPG-U, had over a 0.5 tCO_2e difference in credits per stove. At the much larger project scale, even small differences in carbon credits calculated based upon differences in the value of the *f*NRB applied, can have huge impacts potentially greatly changing the amount of income earned. In general, the biomass stoves seem to perform relatively better than the fossil fuel stoves at lower values of *f*NRB. Therefore even though the fossil fuel stoves obtain high values of carbon credits when employing high values of the *f*NRB, if the *f*NRB was low, such projects may not make financial sense in the context of carbon credits.

The current high levels of fNRB in actual projects may reflect the fact that: a)cookstove projects at lower levels of fNRB are simply not financially viable, b)the flexibility in methods and uncertainties in data allow project developers wide latitude in determining the fNRB and therefore maximize their carbon credits, or c)a combination of both these potential influencing factors. If uncertainty in the calculations of the *f*NRB was reduced and actual values of the *f*NRB were deemed to be lower than the current high values, this could significantly change the amount of credits calculated in all scenarios. As the uncertainty and lack of specific guidance for calculating this number may be resulting in inaccurately reported emission reductions (Johnson et al., 2010), this is an area where more research is needed to reduce the uncertainty incorporated in these values.

5.2.3 Propagation of Uncertainty

In the two prior sections, uncertainty linked with both BC and *f*NRB variables was discussed. It is important to point out that when carbon credits are calculated the uncertainties in all variables are compounded. The specific levels of uncertainty associated with variables which disproportionately impact the outcomes in the number of credits calculated will have the largest impact (e.g. BC). Again there are tradeoffs between efforts to obtain estimates and the estimates' accuracy. The inclusion of CDM's default EF, reduces the efforts required, but is misrepresentative of actual emission reduction interactions. Still this default provides a conservative estimate. For variables such as the *f*NRB and especially BC, which both can considerably determine the amount of credits calculated, such tradeoffs need to be addressed in conversations about developing expectable methodologies that are conservative and as representative as possible.

5.3 Reducing Already Low Levels of Exposure?

The application of Pope et al. (2009)'s dose-response curve to represent IAP impacts has a few important implications worth noting. In Smith and Peel (2008)'s work using the dose-response relationship to estimate impacts of IAP on CVD, the greatest relative risk reduction occurs when switching from low levels of exposure (1 mg/day) to even lower levels of exposure (0.1 mg/day). This implies that to have the largest impact on health, efforts should be focused on reducing already low levels of exposure to become even lower. As this relationship is extrapolated for IAP, stronger, empirical support is needed to confirm this. Still if such a relationship holds true it could have significant and perhaps unintuitive consequences for policy if health is a major priority. Namely, it would imply that the switch from traditional stoves to marginally improved biomass stoves would not result in significant health improvements.

5.4 Maximizing Climate and Health Benefits

The best three stoves for maximizing climate and health benefits in this analysis were the W-Fan-U[17], Kero-U, and LPG-U stoves, with W-Fan-U being the only possible certifiable option under the CDM. For estimated health benefits, the individual exposure from all three stoves was below 1 mg/day, with Kero-U having the lowest exposure at 0.32 mg/day. As kerosene has other health and safety concerns associated with its use, such as poisoning, carcinogenic effects and higher risk of explosion (Mehta and Shahpar, 2004), LPG is a preferred fuel from an overall health perspective. However, there is a higher cost associated with its use and it requires a functional fuel supply chain as compared to the solid fuel stoves. W-Fan-U

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[17] This study used a different $PM_{2.5}$ EF for the W-Fan-U stove than the one employed for the same stove in Grieshop et al. (2011) and therefore it has a higher health performance in this analysis in comparison with Grieshop et al.'s (2011) results. There still remains uncertainty in these values as these EF values rely on a limited set of EF studies. Better EFs are need for more accurate calculations.

is the cheapest technology among the top three stoves, but still is more expensive than simpler models of ‘improved’ biomass stoves.

The measurements of EFs used in this analysis were from WBTs either in the lab or in the field, and are not reflective of actual in-home cooking. Therefore actual emissions will likely be higher than represented in this study. There is a greater chance this effect will be stronger for the W-Fan-U stove than the fossil fuels stoves as the W-Fan-U burns wood, a less clean burning fuel with higher variability depending on type of wood and moisture levels. Still W-Fan-U performs better than other forms of ‘improved’ biomass stoves, which would probably also experience increases in their emissions during in-home cooking.

Another consideration not integrated into this study’s estimates is differences in stove tending requirements. If for example the biomass stoves require more time tending to the fuel than fossil fuel stoves, this may increase the exposure increasing the potential for negative health impacts. As there are many variables such as this one impacting actual exposure and resulting health impacts, the results and finding in this study only provide a relative comparison between the technologies included.

Char-U is a much cheaper technology and burns relatively cleanly with a decent level of health benefits, but has very high emissions associated with its production. Therefore it would only make sense as a carbon credit project if switching from a less improved charcoal stove to a more improved charcoal stove. This also holds true for the coal stoves, which had low or negative carbon credits, requiring a switch from less improved coal technologies to more improved coal technologies if applying for carbon credits. For health benefits vented stoves do well compared to similar non-vented stoves as some of the $PM_{2.5}$ emissions are being diverted outside, though this still may have health impacts resulting from ambient air pollution, especially if in a densely populated area (Zhou et al., 2011; Wilkinson et al., 2009).

As switching to fossil fuel stoves from a traditional biomass stove is not possible under the CDM framework it would not be possible to have the highest levels of health benefits under this methodology. Though health improves in all scenarios when switching from the traditional stove, with the exception of the Coal-U stove, the actual resulting health impacts can only currently be very roughly estimated.

There is a need to have a more affordable stove technology that can maximize climate and health benefits to similar levels as the top three performing stoves included in this study's analyses or a viable means to either reduce costs or influence user prices for these stoves. This will be dependent upon a number of other considerations including access to fuel, appropriate technology design and effective distribution models in the specific project locations.

5.5 Fostering Sustainable Development

There are many additional dimensions influencing sustainable development outcomes that are not in the scope of this research which also need to be taken into consideration when implementing cookstove projects (See Simon et al., 2012; Bumpus, 2011). In the context of this study the co-benefits of improving both climate and health conditions are shown to be achieved in almost all scenarios except when switching to the coal and charcoal stoves. Yet there is still a tradeoff between the maximization of these co-benefits. Some technologies create higher levels of climate benefits, and others health. Carbon credit projects inherently take climate benefits into consideration as their measure is in the amount of CO_2e reduced, but development benefits including health are not integrated into this mechanism. Therefore additional efforts need to be made to ensure that projects' priorities are transparent and evaluated for specific outcomes instead of claiming 'win-win' benefits, while failing to recognize the potential tradeoffs between positive co-benefits. Decisions involved in choosing project technology and determining project design must be consciously made to ensure that there are limited tradeoffs of benefits in order to cultivate actual win-win projects. Additional considerations also need to be taken into account to ensure sustainable development outcomes such as local environmental impact, local users needs and levels of participation, and how benefits of carbon credits are distributed to foster equitable outcomes. The GS framework is intended to ensure higher levels of sustainable development, but as this study shows it does not always account for all the various tradeoffs possible for a given priority area.

6 CONCLUSION

In this study it was found that tradeoffs do exist between the maximization of co-benefits for the number of carbon credits calculated and health outcomes. Therefore if GHG reductions or improved health are significant priorities these need to be explicitly addressed to ensure direct results. Three technologies were identified that provide both high climate and health benefits, the Kero-U, LPG-U and W-Fan-U stoves. However, their distribution is limited due to their high costs. Additionally, the fossil fuels stoves if switching from a biomass stove, can only be certified under the GS voluntary emission credits methodology and require established fuel supply chains. If feasible, there is a need for more affordable biomass stove that consistently achieves these emission levels in order to address health concerns on a larger scale. Carbon credits provide the opportunity to potentially subsidize these projects, but as health or other development benefits are not inherently accounted for under this mechanism these issues need to be individually and directly addressed under this framework.

Within the carbon credit framework further tradeoffs are identified as the GS methodology consistently calculated more carbon credits than the CDM. Still the actual profitability of such projects will be greatly dependent on the price the credits are sold for, cost of certification, size of the project and demand for specific types of credits. Additionally, the CDM's equation does not reflect actual emission reduction processes as accurately as GS and uses a misrepresentative default baseline EF in its calculations. Other considerations regarding carbon credit calculations are the potential inclusion of BC and the accuracy with which *f*NRB is determined as both greatly influence the number of credits calculated. BC has the potential to greatly increase profitability of such projects while also better representing climate forcings in carbon credit calculations. It could also potentially allow for cookstove projects to apply for carbon credits even in areas with low rates of non-renewable fuel sources. For the *f*NRB, as it is a highly sensitive variable, more robust methods are needed to more accurately reflect actual emission reductions.

As implementation of cookstove carbon credit projects is complex and multi-faceted, this research is meant to present further considerations for this process. It is imperative that specific priority criteria are clarified before project implementation for projects framed as 'win-win' to ensure that such priorities are actually achieved.

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