Field Evaluation of Alternative and Traditional Cooking Fuels in Haiti

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D-Lab Scale-Ups

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I Summary

The aim of this study was to perform a rigorous field evaluation of alternative cooking fuel during actual use. *Chabon Vet* (green charcoal) fuel briquettes are produced by Carbon Roots International (CRI) in Cap Haïtien, Haiti and are made from carbonized agricultural waste, predominantly sugarcane bagasse. During this study Chabon Vet was compared to other commonly used wood-derived fuels (wood charcoal and firewood). 93% of Haitians rely on wood and wood charcoal as their primary household energy source. This has resulted in mass deforestation leaving only 2% of Haiti's original forest cover remaining. In addition, Haitians spend, on average, 50% of their income on cooking fuel. CRI is addressing these urgent issues by introducing a renewable alternative to wood fuels made from readily available agricultural waste.

A mobile laboratory was developed and deployed by a team from MIT's D-Lab to perform cooking technology evaluations in and around Cap-Haïtien where Chabon Vet is produced and sold. A modified version of the standard laboratory test method for cooking technology, the Water Boil Test (WBT), was used during the evaluations. The field team set up the mobile lab at a different household each day and worked with stove users to perform the tests. This method is unique in that it utilizes the advanced measurement methods commonly used in controlled laboratory testing, but brings the laboratory to the home and involves the user to incorporate local practice and behavior into the test.

A total of 57 individual WBTs were performed in seven different households and one commercial setting (restaurant). Of the 57 WBTs performed, 44 were completed successfully. Three different fuels (Chabon Vet, wood charcoal and firewood) and eight different cookstoves were tested.

The averaged test outputs from this study show that in general Chabon Vet performs similarly to conventional wood charcoal in terms of practical use, efficiency (Figure 1) and emissions indicators (Figure 2). Use of Chabon Vet in both traditional and improved stoves requires more time to complete the WBT compared to wood charcoal due in large part to its lower net calorific value (also referred to as lower heating value). At the same time, the average burn rate and firepower of stoves using Chabon Vet are 30-45% lower than stoves using wood charcoal, which results in more efficient heat transfer from the burning fuel to the pot (thermal efficiency). The average dry fuel consumed during the WBT was nearly equal for Chabon Vet and wood charcoal despite the large difference in calorific value.

Measurement of respirable particulate (PM10) and primary gas phase emissions (carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen oxides) were obtained during each test in this campaign. These results reaffirm previous findings which show that the use of carbonized fuels produce significantly lower PM10 emissions than firewood, achieving 2-3 orders of magnitude reduction. Emissions factors of CO_2 from use of Chabon Vet are on average 29% lower than wood charcoal. Emissions of CO for both Chabon Vet and wood charcoal are higher than for firewood used in a three-stone fire.

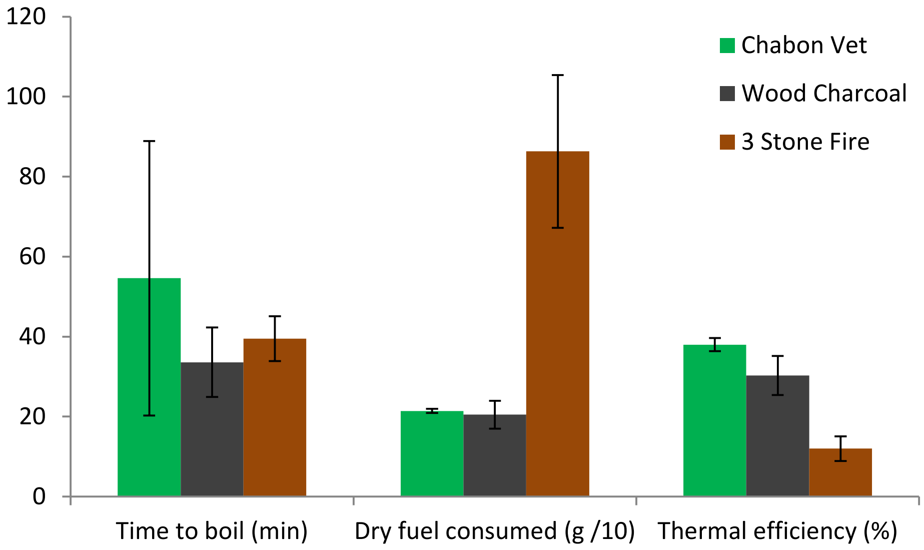

Figure 1. Aggregated performance results from evaluations of Chabon Vet, wood charcoal and firewood (3 stone fire)

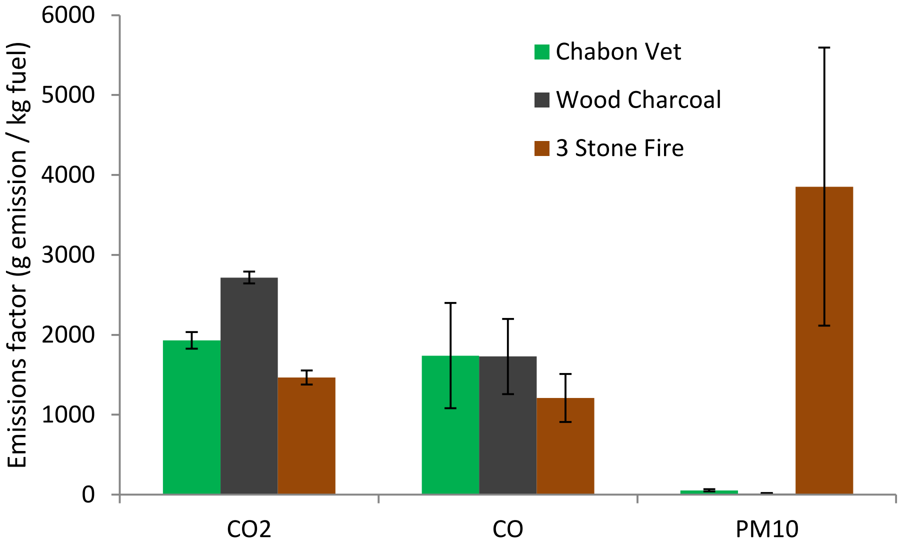

Figure 2. Aggregated emissions factors results from evaluations of Chabon Vet, wood charcoal and firewood (3 stone fire)

Within the International Standards Organization (ISO) International Working Agreement 11-2012 (IWA 11) cooking technology testing framework, Chabon Vet performed slightly better than wood charcoal within the same stove category. Overall, Chabon Vet used in improved cook stoves exhibited the highest IWA 11 tier ratings of all fuel-stove combinations tested. In particular, carbonized fuels demonstrated high tier rankings (Tier 3-4) in PM10 emission factor, PM10 indoor emissions and thermal efficiency. Chabon Vet and wood charcoal both rated Tier 0 or Tier 1 in CO emissions factor, CO indoor emissions and specific fuel consumption. Insufficient combustion air supply and surface ash accumulation can account for the elevated CO production.

Standard deviations of many of the Chabon Vet test outputs are significantly higher than for wood charcoal or firewood, indicating more variation in performance, which could be attributable to variation in the briquettes themselves, or more likely user unfamiliarity with the product. A significant difference between Chabon Vet and wood charcoal is their net calorific value, which for Chabon Vet is 25% lower than wood charcoal. The high ash content of Chabon Vet is a contributor to this, though the study results show that there was not a negative impact on fuel consumption and efficiency.

The use of improved, insulated stoves was shown to make a large impact on stove performance and emissions. Thermal efficiency increased by 60-70% and fuel consumption decreased by 40% for both Chabon Vet and wood charcoal in an improved stove compared to traditional stoves. CO emissions factors decreased by 33-43%, and PM10 emissions factors decreased by 68-95% for both Chabon Vet and wood charcoal used in improved cookstoves. These results show that significant health, environmental and livelihood benefits can be gained by using Chabon Vet coupled with adoption of improved cook stoves.

II Introduction

Globally, biomass accounts for ten percent of energy production, two-thirds of which is used for cooking and heating purposes in developing countries (IEA 2013). Despite increasing access to electricity and modern fuels, consumption of solid biomass fuels continues to increase (FAO 2013). While the combustion of these fuels is generally viewed as a renewable, carbon-neutral energy source, such fuels are generally not harvested or used in a sustainable way. Unsustainable, and often illegal, harvesting of forest resources has resulted in widespread environmental degradation, decreasing fuel availability, and increasing wood fuel costs. Further, the emissions from the generation of charcoal and/or the combustion of biomass can have major negative impacts on human health (WHO 2014a) and regional and global climate (Bond et al. 2013).

The preferred fuel for many people, particularly in urban populations, is wood-derived charcoal, based on its relatively low smoke emissions and suitability for traditional cooking practices. Conventional wood-charcoal production is accomplished through a low-temperature (500°C) pyrolysis process called carbonization. Trees are felled and the timber is arranged in large piles on site. The piles are ignited, covered with earth and allowed to smolder for up to two weeks in what are commonly referred to as earth mound kilns. The slow, low-temperature conversion of raw woody feedstock to charcoal results in emissions of moisture, gaseous and aerosol wood volatiles, and other products of incomplete combustion (e.g. carbon monoxide, hydrocarbons and particulate matter). The solid residue remaining in the kiln, charcoal, constitutes only 8-12% of the original wood feedstock mass (Kammen and Lew 2005). Approximately half of the energy content in the original wood feedstock is lost during traditional charcoal production due to low conversion efficiency and loss of energy in volatile and gaseous emissions. Therefore, the impact of charcoal production on deforestation and environmental degradation is greater than that from wood fuel harvesting.

93% of Haitians rely on charcoal and firewood as their primary energy source (GACC 2014). As a result of over-harvest without replanting, only 2% of Haiti remains forested today ("Country Profile: Haiti" 2006). Due to limited supply the price of charcoal in Haiti has gradually risen reaching levels higher than in other developing countries, causing Haitian households to spend over 50% of their income on fuel.

A Partners

Carbon Roots International (CRI)[1] is addressing the problems of unsustainable wood fuel harvest and low adoption rate of improved cookstoves by introducing a culturally appropriate wood-charcoal substitute. CRI produces green charcoal, or *Chabon Vet*, by contracting with local farmers and agricultural processors to purchase their carbonized agricultural residues, or biochar. CRI processes the char into briquettes in a mechanized production facility located outside of Cap-Haïtien located on the north coast of Haiti. The facility has a production capacity of ten tons per day of dry briquettes. After processing, Chabon Vet is distributed and sold within and areas surrounding Cap-Haïtien and is cost competitive with conventional wood-derived charcoal.

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[1] www.carbonrootsinternational.org

MIT's **D-Lab**[2] is building a global network of innovators to design and disseminate technologies that meaningfully improve the lives of people living in poverty. The program's mission is pursued through interdisciplinary courses, technology development, and community initiatives, all of which emphasize experiential learning, real-world projects, community-led development, and scalability. Within D-Lab, the Scale-Ups program works with social entrepreneurs from MIT and the developing world, as well as NGOs and corporations, to bring poverty alleviating technologies to market at scale. Through the Harvest Fuel Initiative (HFI)[3], D-Lab Scale-Ups is scaling alternative fuels production and distribution in developing countries, taking charcoal briquettes from informal enterprises to a formal industry providing clean fuel and employment opportunities to communities, and added income to smallholder farmers.

D-Lab's involvement in development and dissemination of technology for production of charcoal briquettes originates from work in Haiti during the early 2000's through "Fuel from the Fields" (A. Smith and Frayne 2003). A simple, low-cost method for converting readily available and unused agricultural waste to char, and char to fuel briquettes was developed and disseminated in Haiti and elsewhere through text and video content created from Fuel from the Fields. Following initial dissemination and adoption by users in a number of developing countries, evaluation of the charcoal making process and, in particular, use of the charcoal briquettes was the subject of in-depth laboratory and field experiments led by D-Lab (Banzaert 2013). These findings showed that carbonized agricultural waste briquettes could be a viable alternative to wood charcoal. However, emissions from briquettes are often higher than from wood charcoal. Further research by D-Lab has shown that carbon monoxide (CO) and particulate emissions (PM) vary depending on the briquette physical properties (shape, density) and composition (ash, feedstock type, volatile matter). In addition, differences in measured performance and emissions have been observed between laboratory and field tests.

In the broader cooking technology research community, much focus has been on stove technology with less work dedicated on cooking fuels. A major benefit of charcoal is the low household air pollutant emissions compared to firewood. However, low-efficiency and high greenhouse gas and particulate emissions during the production phase has been identified in several studies (Kammen and Lew 2005; K. R. Smith et al. 1999; Bailis 2009). Research has also been undertaken to point out challenges and recommended best practices for charcoal briquetting businesses (Ferguson 2012) and selection of suitable feedstock materials (Chardust Ltd. and Services 2004).

B Scope of study

Few studies have rigorously evaluated alternative cooking fuels during the use phase. Evaluating use phase performance is important because it can point out benefits and drawbacks of using a fuel, and user adaptations that might be necessary. Given the wide variety of feedstocks (e.g. herbaceous crop residues, mill residues, invasive plant species) and methods used in charcoal briquette production, generalizing evaluation results across all types of fuels is unreasonable. The overall objective of this study was to evaluate an alternative cooking fuel (CRI's Chabon Vet) in comparison to conventional

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[2] d-lab.mit.edu

[3] www.harvestfuel.org

cooking fuels (wood charcoal and firewood) in a location (Cap-Haïtien, Haiti) using a standard testing method performed (modified Water Boil Test, WBT) in actual use conditions. In order to achieve this, a test campaign was designed and carried out during August 2014 which included use testing of Chabon Vet, wood charcoal and firewood at eight different locations (seven household, one restaurant). Each test was performed with an actual user preparing and tending the cook stove and research staff assembling, maintaining operation of and disassembling the mobile test lab. All tests at a given location were performed in triplicate to account for variation between uses. The benefits of this study will be an understanding of important differences between alternative and conventional fuels in different types of stoves with different users. This will help CRI and other alternative fuel producers to identify benefits of using their alternative fuels and areas in need of further improvement. Ultimately, CRI and other briquette producers hope to gain more confidence in their fuel products and reach larger numbers of consumers.

i Study location

The evaluations performed in this study were carried out at seven households and a roadside restaurant in and around Cap-Haïtien, Haiti (19°45’36”N 72°12’00”W), located on the north coast of Haiti in the Nord Department. Cap-Haïtien is the second largest metropolitan area in Haiti with a population of about 190,000. It is accessible by tarmac road (Route Nationale #1) from the capitol, Port au Prince.

CRI was responsible for arranging the study locations, informing users regarding details of the testing using the WBT, and obtaining their permission to perform tests in their home. The specific location of the households and names of the users will not be disclosed. The households were located in a mix of urban, peri-urban and rural settings.

Figure 3. Map showing CRI’s primary consumer market, Cap-Haïtien, and the location of their production site (Quartier-Morin)

ii Study outputs

In order to achieve this objective, the following outputs are anticipated from this study:

1. Direct comparison of charcoal briquettes, conventional wood charcoal and firewood emissions and fuel efficiency in actual use conditions in Cap-Haïtien, Haiti
2. Quantify the variation in fuel-stove performance across a range of commonly used traditional and improved cook stoves and usage behaviors
3. Understand potential user influence on and shortcomings of existing cooking technology evaluation metrics in the context of cooking practices in Haiti
4. Measure relative combustion properties for unique stove-fuel combinations
5. Analysis of Chabon Vet and Haitian wood charcoal for elemental composition and calorific value

C Materials and methods

i D-Lab mobile cooking technology lab

D-Lab has designed and constructed an apparatus for evaluating household cooking technology in the field. The design of the mobile lab (Figure 4) is similar to that of Aprovecho (Maccarty et al. 2008) with a hood to capture stove emissions and instruments for sampling and measuring gas and particle emissions. The test lab can be packaged into 4-5 large suitcases which meet the requirements of most air carriers for checked baggage (<50 lbs). The mobile lab includes a suite of equipment for measuring quantities which can be correlated to cooking performance and emissions measurement (Table 1). The lab can be unpacked and set up inside a kitchen in less than one hour allowing for daily assembly and disassembly so as to minimize inconveniences on the household. All of the electrical components can operate using either an available electrical connection (120 or 240 VAC), or internal and external battery (12 VDC). An annotated photo of the lab assembled in a home is displayed in Figure 5.

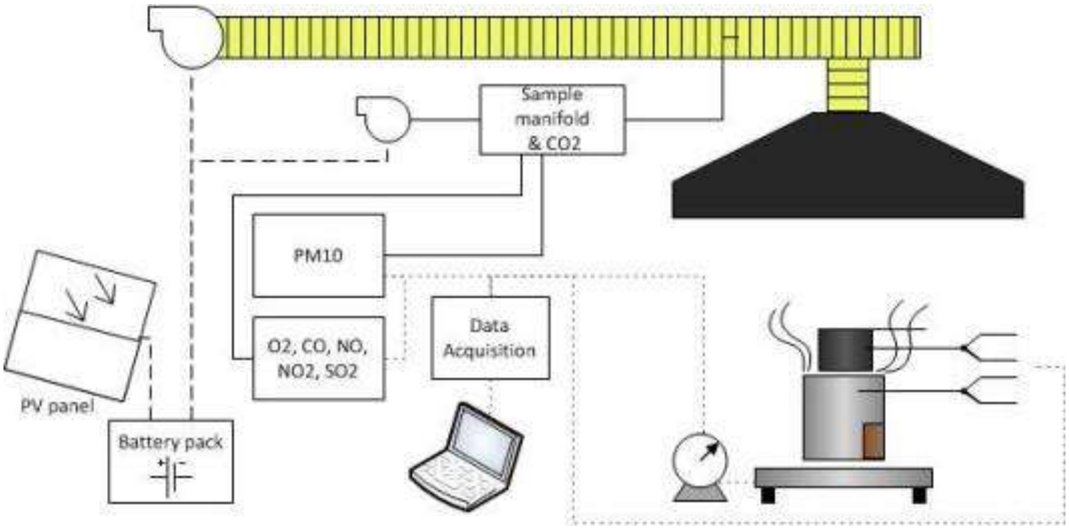


Figure 4. D-Lab mobile cooking technology lab diagram

Figure 5. D-Lab mobile cooking technology lab assembled at a user's home

Table 1. D-Lab mobile cooking technology lab components

Quantity Measured	Instrument	Test outputs
Fuel consumption		
Cooking apparatus mass (g)	Hiweigh Model: WPS III (30 kg x 1 g) scale (120 VAC or battery)	Fuel mass loss (g); Firepower (kW)
Water properties		
Water temperature (°C)	0.125 inch type-K thermocouple, Lascar Model: EL-USB-TC-LCD data logger	Time to boil (minutes)
Water mass (g)	5 kg x 1 g battery powered kitchen scale	Water volume (L)
Stove temperature (°C)	0.125 inch type-K thermocouple, Lascar Model: EL-USB-TC-LCD data logger	Combustion chamber internal temperature (°C)
Stove emissions		
Emissions extraction blower	TRAC Model: T10081, 460 m^3/hour in-line blower, 12 VDC	
Sample vacuum pump	Thomas Model: 107, 21 in Hg max vacuum, 12 VDC	
CO_2 concentration (vol%)	CO2Meter Model: CM-0056 nondispersive infrared (NDIR) CO_2 analyzer, 0-5vol%, nondispersive infrared (NDIR)	Exhaust CO_2 concentration (ppm); CO_2 total emissions (g); CO_2 emission factor (g/kg fuel); Hood carbon balance (mass%)
O_2 (vol%), CO, NO, NO_2, SO_2 concentration (ppm)	Bacharach Model: ECA450 Environmental Combustion Analyzer (electrochemical)	Exhaust gas concentration of O2, CO, NOx, SO2 (ppm); Total emissions (g); Emissions factors (g/kg fuel); Hood carbon balance (mass%)
<10 µm particulate (PM10) mass concentration (mg/m^3)	TSI DustTrak Model: 8530 light-scattering laser photometer	Exhaust PM10 aerosol mass concentration (mg/m^3); PM10 total emissions (g); PM10 emissions factor (g/kg fuel); Hood carbon balance (mass%)

ii Modified Water Boil Test

A number of different standard test methods exist for evaluating cooking technologies in the laboratory and field. These include the Water Boiling Test (WBT) ("The Water Boiling Test Version 4.2.3" 2014), the Controlled Cooking Test (CCT) (Bailis 2004) and the Kitchen Performance Test (KPT) (Bailis 2007). The WBT is commonly used for lab evaluations because it can be easily replicated and the results are generally consistent among different labs. The CCT and KPT are generally used for field evaluations because they require less equipment and are relatively non-intrusive for the user. To accommodate the primary goal of accumulating a relatively large number of comparative tests between different fuel-stove combinations in a relatively short time-frame, with real users and use conditions, a modified version of the WBT has been designed. Performing field WBTs also allows for better comparison between alternate fuels produced in different locations and applied in different use practices. However, supplemental testing using the CCT and KPT methods are recommended to verify and supplement results from WBT testing.

The modified WBT method used in this study closely follows the standard WBT protocol, with several exceptions:

1. Users are allowed to prepare and ignite the stove using their preferred method. Ignition methods included hot embers from other stoves, high-pitch pine wood and polyethylene bags. Users were also allowed to decide how much fuel to add to the stove with instruction that it should be suitable for consecutively boiling two pots containing 3 L of water each.
2. During fuel ignition, many users prefer to leave the cook stove outside so that it is well-aerated and ignites more quickly. This practice was permitted for these tests so as not to conflict with common practice. Therefore, ignition phase measurements were generally not obtained.
3. 3 L of water are boiled to accommodate the smaller, household-scale stoves evaluated in this study. 5 L tests have been performed in the past and smaller stoves were not always able to bring the water to a boil.
4. A lid was used on the pot in order to reduce heat and evaporative water loss from the pot, and time to boil. During previous lab testing, it was observed that heat loss from the pot due to evaporation resulted in a prolonged time to boil when the charcoal burn rate is low. Since charcoal stoves are batch fed, the heat output from the burning fuel is not constant and there is little control over the firing rate. In real use conditions, users often utilize lids to minimize heat loss and prolong the useful duration of a given fuel batch burn. For these reasons a lid was used during this study.
5. In addition to carbon dioxide (CO_2), carbon monoxide (CO), respirable particulate (PM) and other pollutants commonly emitted from combustion devices are measured. These include nitrogen oxides and sulfur dioxide. These pollutants are important from an environmental standpoint, and the D-Lab mobile lab includes equipment to measure them. Pollutant emissions are discussed in more detail later in this report.
6. The low-power, simmer test phase was excluded in this study because low-power operation in charcoal stoves is difficult to achieve in a controlled manner and not commonly desired by users. This is mostly due the fact that charcoal stoves are typically batch operated, and therefore the

user has little control over fuel combustion. Reduction in cooking temperature is especially challenging with improved, clay-lined charcoal stoves because the clay liner provides sufficient thermal inertia to maintain high temperatures in the stove even if fuel combustion is producing little heat. Excluding the simmer phase also reduced the total test time and potential for test failure which were concerns since minimizing time at a given household was a priority.

7. Ash residue remaining at the end of the test is assumed to be free of charcoal. Based on observation, this assumption is generally true, however on occasion small amounts of charcoal fines settle at the bottom of the stove and remain unburned. This assumption should be verified through analysis of ash from charcoal stoves.

iii Test procedure

The following is an overview of the modified WBT used in this study. It is assumed that the user has been briefed prior to the test regarding the expectations for their involvement in the test, which is primarily tending to the stove according to their normal practice. The WBT protocol method ("The Water Boiling Test Version 4.2.3" 2014) includes three phases of stove operation during which two pots of initially cold water are consecutively boiled ("cold start" and "hot start" or "high power" phases) and then the second pot is maintained at a simmer ("simmer" or "low power" phase). The modified WBT used in this study does not include the simmer phase because low power cooking with charcoal is not common and the test duration is shorter, allowing for a greater number of tests within a given day at each home. For the remainder of this report the first test phase is referred to as the "cold start" and the second phase is referred to as the "hot start" in accordance with the condition of the cook stove.

Modified WBT procedure:

1. Arrive at user's home. Make introductions and review the test plan and roles of those involved.
2. Discuss and verify the location of the tests. Unpack and assemble testing apparatus, making sure to first check with and get permission from user when moving or rearranging in and around their kitchen.
3. Gather the stove(s) to be used for the days testing and record empty stove masses. This is preferably the user's own stove which they are familiar with operating.
4. Gather the fuel(s) to be used for the day's testing. This is provided by and paid for by the testing team, not the household. Make sure the user is familiar with use of the fuel(s).
5. Ensure that a supply of water is available nearby and fill a jerrycan or other large, watertight container with fresh water.
6. Fill the pot with 3 L (approximately 3000 g) of water.
7. Begin instrument operation to measure background emissions levels in the room for at least five minutes.
8. Stove preparation and ignition:
    a. User loads a batch of fuel into the stove.
    b. Measure initial fuel mass.
    c. User ignites fuel using their preferred method.

    d. When the user indicates that the stove is ready for use, move the stove to the measurement platform to begin phase 1 of the test. Take care while moving the stove with hot, burning fuel inside it. Wear well-insulated gloves and clear a walking path.

9. Cold start (CS) phase:
    a. Measure the initial fuel + stove mass by placing the stove on the high-capacity scale (make sure the scale platform is protected with an insulating board).
    b. Place the pot of water on the stove, start the test timer and begin regularly recording the stove+fuel mass.
    c. Perform a pot lift every five minutes to isolate changes in fuel mass from changes in water mass.
    d. Once water reaches boiling, record the time to boil, remove and weigh the pot+water and begin the next phase.
10. Hot start (HS) phase
    a. Ask the user if they would like to collect the boiling water for tea, cooking or bathing. Quickly empty and replenish pot with 3 L of fresh water.
    b. User inspects the stove and determines if it requires agitation, fuel addition or another alteration.
    c. Place pot of water on stove, note test hot start phase start time and resume recording stove+fuel mass with intermittent pot lifts.
    d. Once water reaches boiling, record time to boil. User and test team either extinguishes fire or uses stove for other cooking task. Again, ask if the user would like to collect the hot water.
11. Collect 5 minutes of post-test measurements to confirm background emissions levels.
12. Repeat this procedure to obtain triplicates using each type of fuel/stove.
13. At the end of the day, disassemble and repack mobile lab.
14. Thank the user and other household members. Offer a gift if advised to by the local partner. Leave any extra fuel as an additional token of gratitude.

iv Description of pollutant emissions measured

The WBT recommends that CO_2, CO and PM2.5 are measured during the test. In addition to these, sulfur dioxide (SO_2) and nitrogen oxides (NO, NO_2, cumulatively referred to as NO_X) were measured during tests in this study. It should be noted that levels of pollutant exposure to humans and room emissions concentrations were not measured. Rather, total pollutant mass and real-time duct concentrations are reported which allow for easier comparison between tests. The following is a discussion of the type and significance of the pollutants measured.

- **CO_2** (carbon dioxide) is generally the highest yielding combustion product and is produced predominantly through the carbon oxidation reaction mechanism ($C + O_2 \rightarrow CO_2$). CO_2 in the exhaust gas from any combustion device can be used as relative indicator of combustion intensity, or firepower. The higher the CO_2 concentration the greater the intensity of the fire and rate of fuel consumption. CO_2 is an inert gas at standard temperature and atmospheric pressure and poses no significant health risk unless it displaces air which can result in asphyxiation at concentrations of 7-10 vol%. CO_2 is a greenhouse gas due to its ability to absorb outgoing infrared radiation from the Earth's surface resulting in increased temperature of the atmosphere. CO_2 remains in the atmosphere for approximately 100 years and is absorbed through dissolution into the ocean or plant growth through photosynthesis.

- **CO** (carbon monoxide) is a primarily formed as the product of partial oxidation of carbon ($C + ½O_2 \rightarrow CO$). The presence of CO in the products from a combustion device indicates global or local incomplete combustion generally due to insufficient availability of oxygen. CO itself is a combustible gas ($2CO + O_2 \rightarrow 2CO_2$ + heat). However in many combustion devices like cook stoves, the concentration of CO in the exhaust gases is below the lower flammability limit of CO (12 vol%). CO is highly toxic because it combines with hemoglobin forming carboxyhemoglobin (COHb) and displacing sites where oxygen attaches to hemoglobin for transport to organs throughout the body. Chronic CO exposure is also believed to result in chronic ailments in the cardiovascular and nervous systems. The WHO recommended maximum exposure levels for CO are 30 ppm for one hour and 90 ppm for 15 minute time periods (WHO 2010).
- **PM** (particulate matter) can be introduced into air through several mechanisms including sediment entrainment and combustion of hydrocarbon fuels. Health risks associated with airborne PM are related to the particle size. Of particular concern or particles smaller than 10 micrometers (microns) in size, referred to as PM10, which are inhalable and can enter deep into the lungs and cardiovascular system, contributing to a variety of health problems including respiratory disease and asthma. Inefficient biomass cook stoves and open fires emit large amounts of PM10 and fine particulate (PM2.5) which, coupled with other household and ambient air pollutants, contribute to 7 million premature deaths per year worldwide (WHO 2014b). The WHO guideline for maximum exposure to ambient PM10 is 50 $\mu g/m^3$ (WHO 2005). In addition, fine particles commonly referred to as soot or black carbon (BC) are produced from incomplete combustion of carbonaceous fuels. BC emissions are a significant concern not only because of their adverse health effects when inhaled, but also because they become entrained in the atmosphere and are highly absorptive of solar radiation, about one million times more than carbon dioxide. The major global sources of BC are open biomass burning (35.5%) and residential cooking and heating in Asia, Africa and Latin America (25%) (Lamarque et al. 2010). BC emissions, unlike CO_2, are short lived, remaining in the atmosphere for only a few days to a few weeks. Therefore, reducing BC emissions could have an immediate impact on climate change.
- **SO_2** (Sulphur dioxide) is produced naturally from geothermal activity, including volcanoes, and anthropogenically from combustion of fuels containing sulfur ($S_{fuel} + O_2 \rightarrow SO_2$). SO_2 reacts with water vapor in the atmosphere to form sulfuric acid (H_2SO_4), a constituent of acid rain. Short-term and prolonged exposure to SO_2 can result in a variety of adverse respiratory effects. SO_2 is the major component in total sulfur oxide emissions from hydrocarbon fueled combustion processes, which are commonly referred to as SO_X. The WHO guidelines for maximum exposure to SO_2 is 8 ppb over 24 hours and 190 ppb over 10 minutes (WHO 2005).
- **NO_X** (nitrogen oxides) is produced from the oxidation and partial oxidation of hydrocarbon fuels in air under high-temperature conditions. NO_X is considered a harmful environmental and

health pollutant for several reasons. The two major NO_X components, NO and NO_2, react in a cyclic, rapid set of reactions catalyzed by sunlight forming each other and elemental oxygen (O) which goes on to form ozone (O_3), a contributor to smog. In addition, NO_X reacts with water vapor in the atmosphere to form nitric acid, a component in acid rain. Short-term and prolonged exposure to NO_X is linked to adverse respiratory effects. The WHO guideline on maximum exposure to NO_2 is 106 ppb over 1 hour (WHO 2005).

v Description of fuels and stoves tested

Since the primary objective of this study was to gain an understanding of the comparative performance of Chabon Vet and wood charcoal, these were tested exhaustively. Home visits 1-7 focused on triplicate WBTs for each fuel. A sufficient amount of Chabon Vet was on hand throughout the campaign to complete triplicate tests in a given day. The user was allowed to select their preferred type of wood charcoal since several types are available. A member of the research team would then gather that type of wood charcoal from a nearby sales point. In general, most users preferred the highest-grade wood charcoal, which was sampled and analyzed, the results of which are presented along with those for Chabon Vet and firewood in Table 2. Proximate and ultimate analyses were performed according to ASTM standards. Definitions of key fuel characteristics are provided:

- **Volatile matter**: Fuel undergoes sublimation or melting and is released from the fuel as a vapor (essentially boiling oils from the fuel sample) when introduced to sufficiently elevated temperature conditions. In the standard ASTM test (D3175), volatile matter is defined as all fuel components that volatilize at or below 950°C.
- **Fixed carbon**: Non-volatile, combustible material (comprised mostly of carbon, sometimes referred to as “char”) remaining in the fuel after volatile matter is released. For charcoal, the fixed carbon content is normally high since the carbonization process results in the release of moisture and volatile matter. Fixed carbon does not include the inorganic, non-combustible ash component of the fuel that remains following the carbon burnout in the standard ASTM test (D3174).
- **Ash**: Inorganic, non-combustible component of the fuel. For biomass, ash typically consists of large quantities of plant nutrients including silica, calcium and potassium. Ash content in most charcoal briquette fuels is greater than wood charcoal because most of the fuel binder remains as a residue during fuel use. See (BISYPLAN 2012) for more information on biomass ash composition and analysis.
- **Net calorific value (lower heating value, LHV)**: The heat of combustion of the fuel minus the heat of vaporization of the water vapor in the fuel and combustion products. Unlike the gross calorific value, or higher heating value (HHV), the energy remaining in water vapor products (heat) is considered unrecoverable. The combustion of carbonaceous fuels like charcoal briquettes is highly exothermic (heat producing) due to the energy release from breaking strong carbon-carbon bonds in the fuel. The calorific value of wood is lower than that of charcoal because of the high oxygen and hydrogen content which release less energy when cleaved from molecular chains and oxidized.

Table 2. Types and properties of fuels tested

	Chabon Vet (green charcoal)		**Chabon bois (wood charcoal)**		**Firewood[a]**	
Proximate analysis, dry (mass%)	Fixed carbon:	52.3	Fixed carbon:	77.3	Fixed carbon:	16.9
	Volatile matter:	18.1	Volatile matter:	10.5	Volatile matter:	82.6
	Ash:	23.5	Ash:	7.7	Ash:	0.5
Ultimate analysis, dry (mass%)	C:	65.4	C:	86.3	C:	48.3
	H:	2.5	H:	1.9	H:	5.9
	N:	0.5	N:	0.7	N:	0.2
	S:	0.3	S:	<0.1	S:	<0.1
	O:	7.8	O:	3.4	O:	45.1
Net calorific value[b], dry (MJ/kg)	21.9		29.3		18.2	
Number of tests reported	20		18		6	

[a] Assumed to be eucalyptus as reported by users during the study. Thermodynamic data gathered from (Domalski, Lobe Jr., and Milne 1986)

[b] Also referred to as lower heating value (LHV)

Table 3. Description of stoves used during testing

								
	Stove 1	Stove 2	Stove 3	Stove 4	Stove 5	Stove 6	Stove 7	Stove 8
Day #	1	2	3, 4, 5	4	6, 10	7, 8	7, 8	8, 10
Fuel type	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal	Firewood
Intended use	Institutional	Household	Household	Household	Household	Household	Household	Household
Construction	Mild steel square-stock, rebar fuel basket	Sheet metal	Sheet metal	Sheet metal, galvanized sheet fuel basket	Sheet metal	Sheet metal (sheath), clay (liner)	Sheet metal (sheath), clay (liner)	3 stone
Notes	Difficulty arranging stove on weighing platform. Ash residues dropped onto weighing platform	Rebar pot supports added at recommendation of user (continued to use through remainder of testing)	Stove was new prior to testing- paint vaporized during first tests	Galvanized coating volatilized during first test- use of stove was discontinued due to safety risk concerns		Recho ajil: International Lifeline Fund clay-lined improved charcoal cook stove supplied by local stove builder	Clay-lined improved charcoal cook stove supplied by local stove builder	3 stone fire prepared on cooking platform by applying a layer of soil on top of an oil drum lid

III Results and Discussion

A Example WBT dataset (05-CV-01)

i Test 05-CV-01: Chabon Vet in a simple cookstove

To illustrate trends of measured values during a typical WBT, timeseries for water temperature, particulate and gas emissions, and relative combustion completeness (CO/CO_2 ratio) for test 05-CV-01 are presented in Figure 6.

Graphs (A) and (B) shows the water temperature timeseries for the 3 L water volume in the pot on the cook stove used as a calorific indicator of useful energy for each test. The end of the test phase is signified by the water reaching its boiling point (approximately 100°C).

Graphs (C) and (D) shows the mass concentration timeseries of respirable particulate (PM10) in the bulk flow collected in the emissions collection hood. This is not room or local concentration for PM10, so the measured values cannot be directly correlated to exposure levels.

Graphs (E) and (F) shows the volume concentration in the collection duct of gas phase emissions from the cook stove. Again, these do not represent room or personal exposure concentrations. The high oxygen (O_2) concentration indicates that the majority of the sampled gas is room air, and not exhaust from the cook stove. This results in emissions dilution, which maintains concentrations in the measurable range for gas and particle analyzers. Background concentrations of each species are measured prior to a WBT and subtracted from measurements during the test. Note that concentrations of O_2, NO_X, and SO_2 are rescaled (see graph legend).

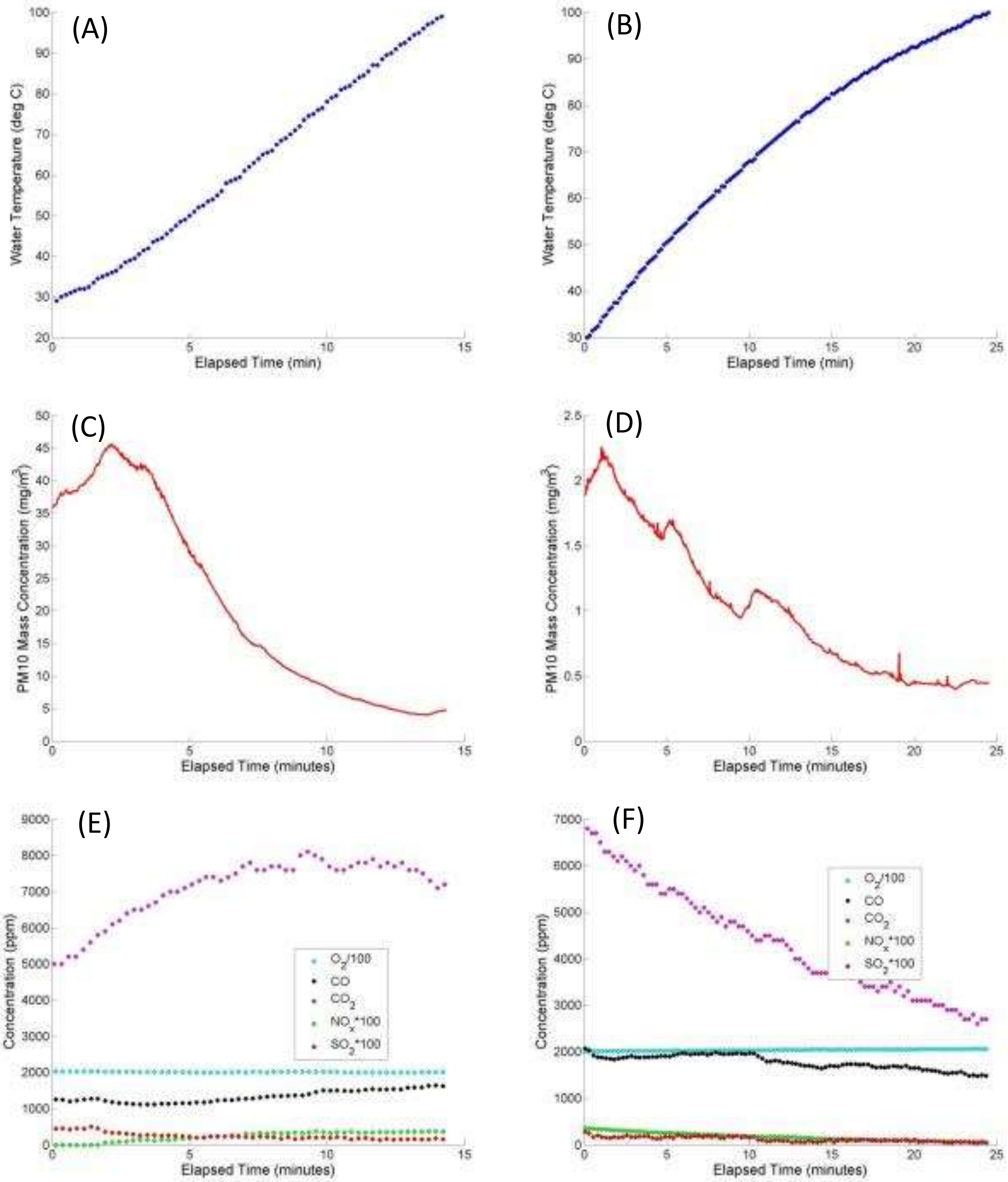
Graphs (G) and (H) shows the ratio of CO to CO_2 (CO/CO_2) through each phase of the WBT. CO/CO_2 provides a relative indication of combustion completeness since CO is a gas phase product from incomplete combustion. Therefore, the lower the CO/CO_2 value, the more complete the combustion process, approaching zero for complete combustion. For comparison, modern household devices which utilize natural gas or propane (e.g. boiler, water heater, furnace) operate near $CO/CO_2 = 0.004$ ($[CO_2] = 250*[CO]$).

In general, batch loaded, packed bed charcoal stoves exhibit similar trends during a WBT, which are discussed below. The measurement trends from test 05-CV-01 will be used to discuss three proposed phases of batch loaded charcoal stove operation, which should not be confused with the cold and hot start phases of the WBT. From most of the tests performed, including 05-CV-01, it is evident that the cold and hot start test phases capture the dominant phases of stove operation. However, it is possible that there are subsequent phases occurring later in the burn and not captured within the typical 30-60 minute duration of the WBT.

Ignition phase: During stove ignition, the fuel burn rate and stove heat output are relatively low resulting in slow initial water temperature ramp (Figure 6A). CO_2 emissions (Figure 6E), which are relatively low but increasing during ignition, can be used as an indicator for combustion intensity. For natural draft stoves like the stoves tested during this campaign, oxygen is made available in the combustion zone by replacement of exiting, hot exhaust gases with an induced draft of air. At ignition, the flow rate of exhaust gases is low resulting in low induced airflow into the stove, fuel-rich combustion and production of large quantities of CO. The initially high CO/CO_2 ratio is due to the combined effects of fuel-rich combustion and low burn rate. Particle emissions (Figure 6C) are highest during the ignition phase due to low stove temperature, creating conditions conducive to various modes of aerosol formation (e.g. particle nucleation and vapor condensation), and poor conversion of volatile species (e.g. alkenes, aromatics) exiting from the burning fuel. The small amount of fuel-bound elemental sulfur (0.25 mass% for Chabon Vet) is oxidized to produce SO_2 early in the burn process due to the relatively low boiling point of sulfur (440°C). NO_X on the other hand is formed at high-temperature conditions (>1600°C) from oxidation of fuel-bound elemental nitrogen and dissociation of oxygen (O_2) and nitrogen (N_2) in combustion air. Therefore, NO_X production is low during the ignition phase.

Steady burn phase: Following ignition phase, the stove approaches thermal equilibrium during which the rate of fuel combustion and heat transfer to the pot of water is relatively steady. For test 05-CV-01 this occurs during the minutes 5-13 range. This phase is signified by a constant, rapid rate of water temperature increase (Figure 6A), relatively steady CO_2 concentration in the stove emissions (Figure 6E), and occurrence of the minimum in the CO/CO_2 ratio (Figure 6G). It is not fully understood why CO production (Figure 6E) gradually increases during this phase despite plateaued CO_2 output, but this is likely due to cumulative effects of ongoing fuel-rich conditions, buildup of ash on the fuel particles and stove grate blocking entry of reagent oxygen, and activation of chemical reactions which produce carbon monoxide through partial oxidation of carbon at high temperature ($C + ½ O2 \rightarrow CO$). Particle emissions gradually decrease through the remainder of the WBT (Figure 6C-D) since the majority of the fuel volatile content has escaped and temperature conditions are sufficient for inhibiting particle formation with the exception of fly ash elutriated with gaseous emissions.

Burn declination phase: Following the steady heat output phase, the quantity of burning fuel slowly decreases as the overall burn declines. For test 05-CV-01, this begins at minute 13 and continues through the rest of the cold and hot start test phases. The reduction in the rate of water temperature increase and CO_2 production are indicators of burn declination. Maintained, high levels of CO result in a gradual decrease in the combustion completeness indicator (CO/CO_2). Again, this is likely due to the cumulative effects of fuel-rich conditions in the stove, ash accumulation, and partial oxidation of the fuel. Users were asked to assess the condition of the stove and make any necessary adjustments (e.g. agitation, fuel addition) between the cold and hot start test phases. In most cases including test 05-CV-01, no adjustments were made, but during some tests users would stir or shake the stove to settle ash, and/or add fresh fuel to prolong the burn duration.


(A)
Water Temperature (deg C)
Elapsed Time (min)
20
30
40
50
60
70
80
90
100
0
5
10
15
(B)
Water Temperature (deg C)
Elapsed Time (min)
30
40
50
60
70
80
90
100
0
5
10
15
20
25
(C)
PM10 Mass Concentration (mg/m^3)
Elapsed Time (minutes)
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
(D)
PM10 Mass Concentration (mg/m^3)
Elapsed Time (minutes)
0
0.5
1
1.5
2
2.5
0
5
10
15
20
25
(E)
Concentration (ppm)
Elapsed Time (minutes)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
0
5
10
15
$O_2/100$
CO
CO_2
NO_x*100
SO_2*100
(F)
Concentration (ppm)
Elapsed Time (minutes)
0
1000
2000
3000
4000
5000
6000
7000
0
5
10
15
20
25
$O_2/100$
CO
CO_2
NO_x*100
SO_2*100

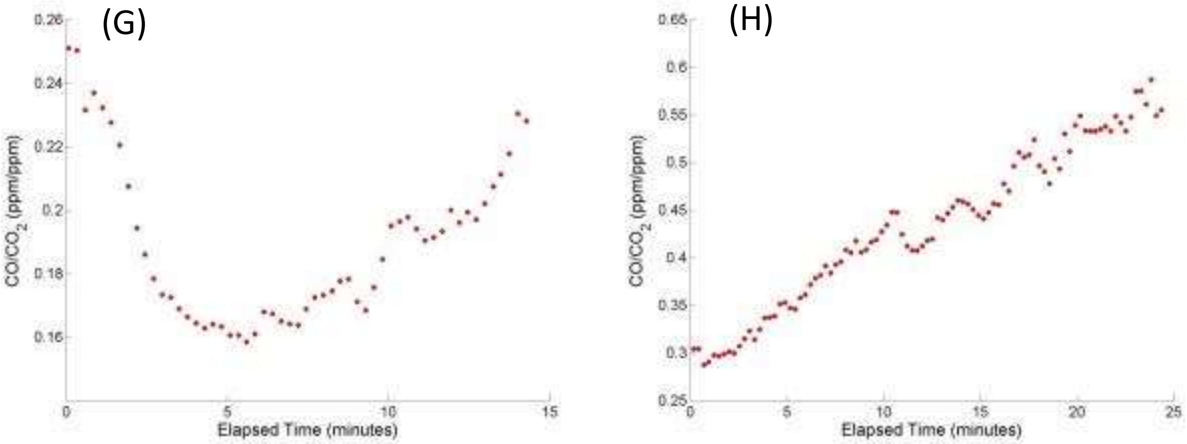


Figure 6. 05-CV-01 timeseries for cold (A) and hot start (B) water temperature, cold (C) and hot start (D) PM10 emissions mass concentration, cold (E) and hot start (F) gas species emissions concentration, and cold (G) and hot start (H) CO/CO$_2$ ratio

Table 4 presents the WBT outputs and International Working Agreement (IWA) IWA 11-2012 ("Guidelines for evaluating cookstove performance") (ISO 2012) metrics for each test phase and overall for 05-CV-01. The IWA performance indicators are adapted from common performance and emissions metrics for cookstoves and are meant to provide a common framework for comparing results from different studies. The five IWA indicators are organized into "tier" rankings (0-4) which are connected to relevant health and environmental studies, "tier 0" indicating poor performance typically associated with a three stone fire, and "tier 4" indicating an "aspirational goal" to each performance indicator. IWA indicator values and tier rankings are reported for test 05-CV-01 (Table 4) and later for each stove-fuel combination (Table 5). Only outputs from tests that were successfully completed, including complete data sets for fuel consumption, water temperature and emissions, were accepted as successful. Practical outputs like time to boil and fuel are included at the top of Table 4. Technical performance and emissions indicators, and IWA tier rankings are situated lower in Table 4.

These test outputs generally reaffirm the observations made from the raw measurement trends previously presented. The cold start test phase includes peak heat output from the stove (maximum in emissions CO2 concentration), therefore, the time to boil was shorter and the fuel and energy consumption were greater than during the hot start phase. In addition, given the >2x fuel burn rate and heat output (firepower) of the stove, but <½ the boiling time during the cold start phase compared to the hot start phase, the overall thermal efficiency of the stove-fuel combination was approximately 30% higher in the hot start phase. While these contribute to the stove-fuel combination achieving a Tier 2 efficiency rating in the IWA framework, the time to boil and other factors, which directly influence user perception of a stove-fuel combination, might not be fully represented. Comparison of these test outputs among various stove and fuel combinations will be discussed in the proceeding section of this report.

Table 4. Test outputs for 05-CV-01

Fuel type	Chabon Vet		
Stove type	Recho simple (#3 in Table 3)		
Test #	05-CV-01-CS	05-CV-01-HS	05-CV-01
Water boil test phase	Cold start	Hot start	Total or Average
Temp. corrected time to boil (minutes)	14.95	26.52	41.47
Dry fuel consumed (g)	140	106	246
Thermal efficiency (%)	30.8	39.8	36.6
Firepower (kW)	3.6	1.5	2.3
Burn rate (g/min)	9.8	4.2	6.2
Temp. corr'd spec. energy consumption (MJ/L H2O)	1072	822	964
CO_2 emissions factor (g CO_2/kg fuel)	1848	1564	1726
CO emissions factor (g CO/kg fuel)	222	408	302
PM10 emissions factor (mg PM10/kg fuel)	3100	200	1850
Average CO/ CO_2 (ppm CO/ppm CO_2)	0.19	0.43	0.34
IWA-11-2012 Metrics (ISO 2012)			
CO emissions (g/MJd) [2]	38.9 (Tier 0)		
PM2.5 emissions (mg/MJd)[1,2]	272.3 (Tier 2)		
Thermal efficiency (%)[2]	34.7 (Tier 2)		
Specific consumption (MJ/min/L)[2,3]	0.054 (Tier 0)		
CO indoor emissions (g/min)	1.79 (Tier 0)		
PM2.5 indoor emissions (mg/min)	10.98 (Tier 2)		

[1] Reported as PM10 measurements, therefore expectedly higher than PM2.5

[2] Averaged over cold and hot start phases and weighted by dry fuel consumed

[3] IWA 11 uses this as a metric for low-power (simmer) phase, which was not included in these WBTs, but the metric is still reported

ii Combustion intensity

Unique trends in combustion intensity for each type of carbonized fuel were consistently observed throughout this study. CO2 concentration in the stove emissions can be used as a measurable surrogate for combustion intensity. CO2 concentration from two full WBTs are displayed in Figure 7, one from a WBT using Chabon Vet (01-CV-01) and one using wood charcoal (01-WC-01). These WBTs were performed in the same household and using the same cookstove. The datasets are relatively noisy, however there are distinct differences in the CO2 emissions trends that are likely connected to physical differences between carbonized briquettes and wood charcoal.

Briquettes tend to ignite slower than wood charcoal. While wood charcoal can have an overall lower content of volatiles matter than briquettes, the production of wood charcoal in earthen kilns results in condensation of volatile matter on the charcoal surface giving it an oily sheen. The flammability of these condensed surface volatiles contributes to easier and more rapid ignition of wood charcoal compared to briquettes.

The combustion intensity of wood charcoal tends to peak and then drop, while that of briquettes tend to plateau and sustain peak intensity. In general, tests with wood charcoal indicated a rapid rise and decay in CO2 emissions/combustion intensity, while that of briquettes exhibited sustained maximum intensity. This characteristic is likely due to a combustion dampening effect from the ash in briquettes which acts as a limiter for surface reactions. It might be a desirable quality for prolonged, moderate-temperature cooking behaviors.

The peak combustion intensity of wood charcoal is higher than that of briquettes. This is the result of a combination of the rapid burn rate and high carbon content of wood charcoal compared to briquettes. During tests using wood charcoal, peak stove output was only briefly maintained before intensity declined.

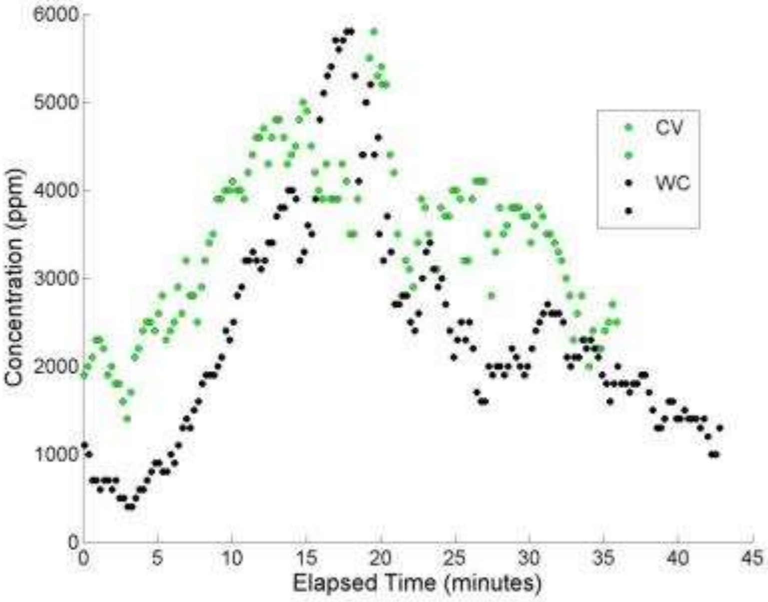


Figure 7. CO2 emission timeseries for cold and hot start phases for tests 01-CV-01 (Chabon Vet) and 01-WC-01 (wood charcoal)

B Aggregated results from Haiti charcoal field study

The following is a presentation and discussion of aggregated WBT results from the entire Haiti charcoal field campaign. Table 5 presents test outputs averaged for each fuel and cook stove type. Table 6 presents test outputs according to IWA 11 evaluation framework. Figure 8-Figure 11 provide a graphical representation of key outputs by fuel and stove type from all successful field WBTs performed in this study. Average test outputs for each stove-fuel combination are indicated by the large markers in Figure 8-Figure 11, are reported in Table 6. The fuels tested were CRI's Chabon Vet briquettes ("CV"), wood charcoal ("WC") and firewood ("3SF"). The stoves tested are categorized as traditional (unimproved, "trad"), improved (clay-lined, "imp"), improved with three stone pot supports ("trad w/ stones"; only tested with Chabon Vet), and three stone fire ("3SF").

i Dry fuel consumed and time to boil

Figure 8 presents cumulative (cold + hot start phases) dry fuel consumed and time to boil for each WBT by fuel stove type. These test outputs are practical in nature since they can be directly connected with user needs depending on factors that are important to the user[4]. Several general observations can be made from these results. In comparison to carbonized fuels (Chabon Vet and wood charcoal), firewood burned in a traditional three stone fire uses significantly larger amounts of fuel (approximately 2.5x more on average) to complete the WBT, but does not complete the WBT in a significantly shorter time (average 5-26% faster). Using both traditional and improved cook stoves, Chabon Vet in comparison to wood charcoal requires a similar amount of fuel (4% more on average) but longer time to complete the WBT (average 24-63% longer). It should be noted that a statistically significant number of tests (3+) were not completed using Chabon Vet in improved stoves, therefore a more accurate estimate of fuel performance in improved stoves can be obtained from further testing. The use of an improved stove resulted in little difference in time to boil, but significantly reduced fuel consumption for both Chabon Vet and wood charcoal (average 40% reduction for both fuels). In addition, the addition of three stone pot supports in a traditional sheet metal cook stove, which was practiced in one household, resulted in a 21% reduction in fuel consumption.

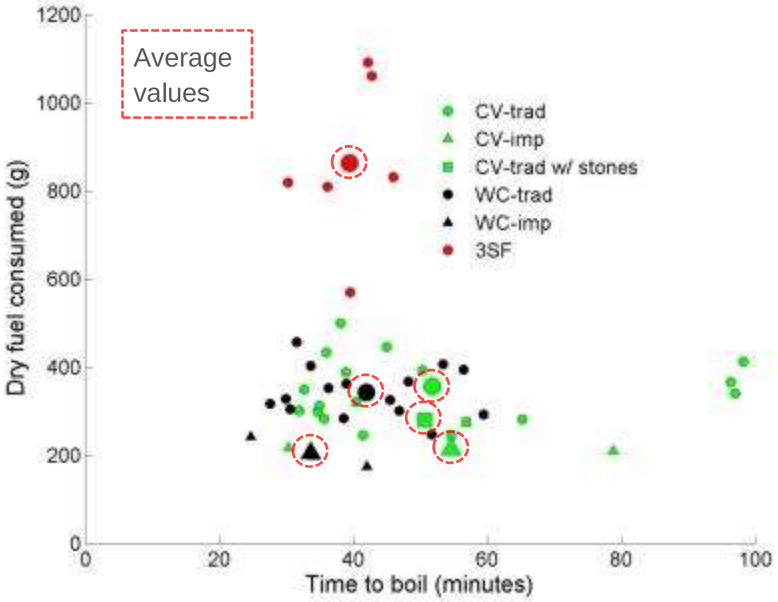


Figure 8. Dry fuel consumed vs. Time to boil for all WBTs performed in Haiti charcoal study

ii Combustion and thermal efficiencies

Figure 9 presents an indicator for combustion completeness (CO/CO_2 ratio) and thermal efficiency averaged over cold and hot start test phases (weighted by time and fuel consumed, respectively) for all stove-fuel combinations. In general, trends over all of the tests performed indicate a correlation between improved combustion efficiency, signified by low CO/CO_2 ratio, and thermal efficiency of the fuel-stove combination. This finding is not surprising since it is expected that complete fuel oxidation to

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[4] This view represents the opinion of the author.

CO_2 results in higher heat output and more efficient transport of fuel energy to energy delivered to the pot. However, stratification of the trend by fuel type suggests that each of the fuels tested have unique characteristics that strongly influence their combustion performance. While this study is not suited to investigate this correlation, it does show that the carbonized fuels tend to achieve higher thermal efficiencies than the traditional three stone fire, though the degree to which fuel is fully combusted is significantly lower. Higher thermal efficiency is expected from carbonized fuels compared to the three stone fire because of the reduced radiative heat losses to the surroundings and lower overall burn rate. On the other hand, skilled operation of three stone fires and fuel rich conditions in charcoal stoves result in large differences in CO emissions and corresponding CO/CO_2 ratios. Ultimately, these results reinforce the fact that efficient combustion of carbonized fuels in natural-draft cook stoves is difficult to achieve. The use of improved (insulated) cook stoves greatly enhances both combustion completeness and thermal efficiency for both Chabon Vet and wood charcoal when compared to unimproved (uninsulated) cook stoves (43% decrease in CO/CO_2 and 57% increase in thermal efficiency for Chabon Vet; 50% decrease in CO/CO_2 and 70% increase in thermal efficiency). On average, cooking with Chabon Vet results in higher efficiency (25-36% higher), but less complete combustion compared to wood charcoal (30-50% higher CO/CO_2). The improved efficiency is likely due to Chabon Vet's lower net calorific value (25% lower than wood charcoal) but little change in mass of fuel required to complete the WBT (i.e. lower net energy consumption per WBT). Less complete combustion for Chabon Vet is likely due to the significant buildup of ash on the fuel and stove liner during the burn, which inhibits interaction of reagent oxygen in the air with the hot surface of the fuel.

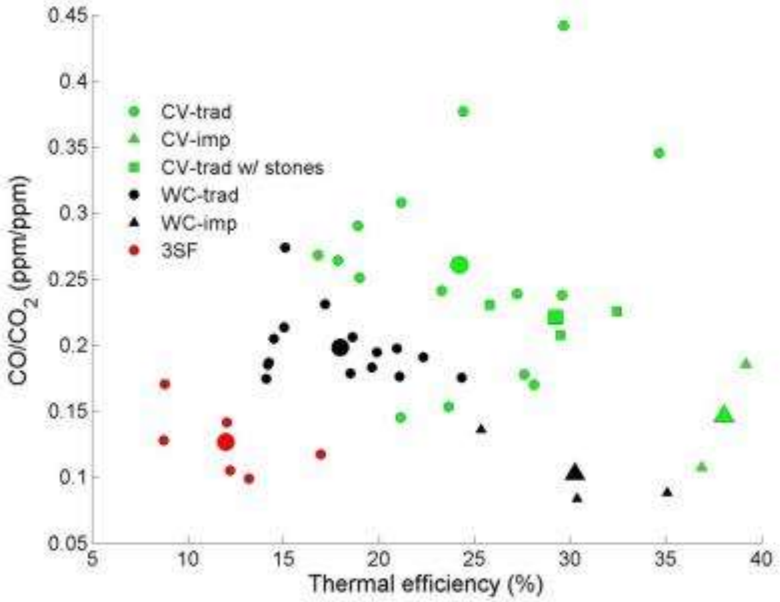

Figure 9. CO/CO2 ratio vs. Thermal efficiency for all WBTs performed in the Haiti charcoal study

iii IWA 11 tier rankings

Figure 10 presents specific fuel consumption and thermal efficiency averaged over cold and hot start phases for all test. Specific fuel consumption provides a normalized value for fuel energy consumed (using the fuel calorific value) per unit time and water volume during a WBT. Both thermal efficiency and specific fuel consumption are used as metrics for evaluating cooking technology in the IWA 11 tier framework (ISO 2012). An overlay of IWA tier threshold values is also represented on Figure 10. Numerical values for these outputs and tier ratings are presented in Table 6. Test outputs used in the IWA tier rating system are typically aggregates of several related measured values. Specific fuel consumption combines fuel consumed and time to complete the WBT and water volume. Thermal efficiency combines burn rate, fuel calorific value and time to boil. It should be noted that specific fuel consumption is used as a metric for fuel use and efficiency during low-power (simmer) stove operation in the IWA framework. This phase of the WBT was omitted during this campaign. However, charcoal stoves general exhibit lower overall heat output, so specific fuel consumption results are considered to be relevant and are included in the reported test outputs.

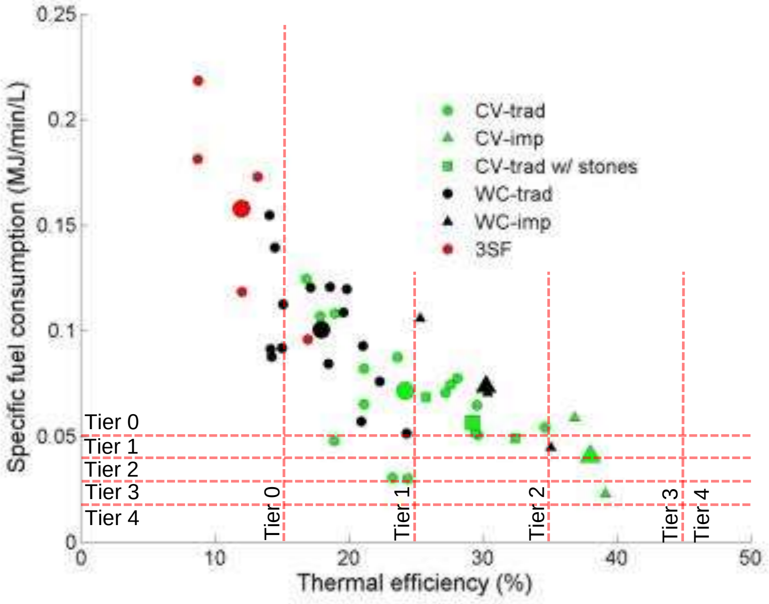

Figure 10. Specific fuel consumption vs. Thermal efficiency for all WBT performed in Haiti charcoal study

It is expected that a fuel-stove combination with low energy consumption will also exhibit high thermal efficiency, which is consistent with the findings of this study. A unique finding from this study is the relatively clear stratification of specific fuel consumption and thermal efficiency performance by fuel type, similar to the arrangement in Figure 9. In addition, the progression of increased fuel and thermal efficiency of each stove-fuel combination follows a near linear or mild exponential decay trend. Despite experienced and careful tending, the three stone fire clearly exhibits the highest specific fuel consumption and lowest thermal efficiency, falling in the Tier 0 rating for both metrics. Continuing along the trend toward lower specific fuel consumption and higher thermal efficiency, Charbon Vet and wood charcoal in unimproved stoves averaged Tier 0 for fuel consumption and Tier 1 for efficiency. From the small number of successful tests run using Chabon Vet in improved stoves, an average of Tier 1 specific consumption and Tier 3 thermal efficiency were achieved, the highest of all fuel-stove combinations tested. Interestingly, the relative combustion efficiency results in Figure 9 suggest that

Chabon Vet does not combust to the same degree as firewood and wood charcoal, but it performs relatively well in terms of fuel consumption and thermal efficiency. This suggests that if the fuel and/or stove were modified to improve combustion efficiency, in other words decrease CO production and increase heat output, performance of Chabon Vet could be further increased.

Figure 11 presents CO and PM10 emissions factors normalized by fuel consumption and calorific value, which are IWA metrics for high power emissions. Thresholds for IWA Tier values are again indicated by the dashed red lines. This data is averaged over cold and hot start test phases weighted by fuel consumed in each phase. Note that the x-axis in Figure 11 (PM10 emissions factor) is scaled logarithmically. Previous studies have shown that three stone fires emit significantly higher quantities of respirable particulate. From results of this study, a three stone fire emits approximately two orders of magnitude higher PM10 than carbonized fuels burned in unimproved stoves, and three orders of magnitude more than carbonized fuels burned in locally-built, improved stoves. Chabon Vet and wood charcoal used in improved cook stoves achieved IWA Tier 3 and 4 ratings for PM emissions, respectively. It should be noted that the WBT and IWA protocols call for measurement of PM2.5 (fine particulate <2.5 µm in size) while this study measured PM10. It's uncertain how significantly this impacted the PM quantities measured, but accounting for PM10 includes PM2.5 plus particles 2.5-10 µm in size. None of the fuel-stove combinations tested achieved better than Tier 0 in terms of CO emissions factor. As previously discussed, efficient and clean conversion of solid fuels in natural-draft stoves is a major challenge. Chabon Vet does show improvements in CO emissions factor compared to wood charcoal (34% reduction in traditional stoves, 20% reduction in improved stoves). However further improvements in both the fuel characteristics and/or stove design is needed to reduce CO emissions and mitigate significant health risks associated with CO exposure.

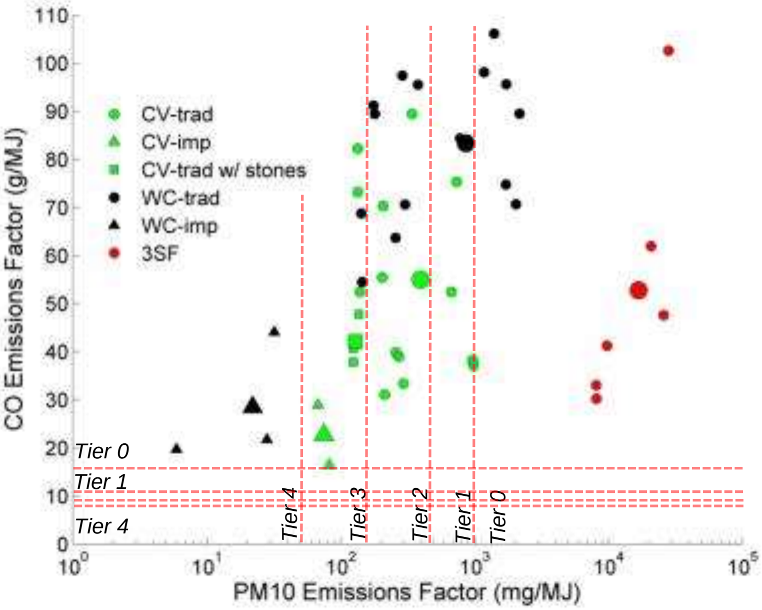

Figure 11. CO vs. PM10 emissions factors for all WBT performed in Haiti charcoal study

Table 5. Average test outputs for each fuel-stove combination presented as "AVERAGE (1 STANDARD DEVIATION)"

Fuel type	**Chabon Vet**			**Wood Charcoal**		**Firewood**
Stove type	Traditional	Improved	Trad + stones	Traditional	Improved	3 stone fire
Number of tests performed	15	2	3	15	3	6
Temp. corrected time to boil (min)[1]	51.8 (25.0)	54.6 (34.3)	50.7 (8.87)	41.9 (10.5)	33.6 (8.66)	39.5 (5.59)
Dry fuel consumed (g)[1]	356 (71.8)	214 (5.21)	281 (37.6)	342 (56.0)	205 (34.7)	863 (191)
Thermal efficiency (%)[2]	24.2 (5.16)	38.0 (1.63)	29.2 (3.35)	17.8 (3.35)	30.3 (4.88)	12.0 (3.07)
Firepower (kW)[2]	3.56 (1.36)	2.04 (1.27)	2.82 (0.52)	5.00 (1.41)	3.66 (1.53)	7.84 (2.19)
Burn rate (g/minute)[3]	9.76 (3.74)	5.59 (3.48)	7.74 (1.42)	10.23 (2.89)	7.49 (3.12)	25.83 (7.23)
Temp. corrected spec. energy consumption (MJ/L)[2]	1584 (406)	918 (30)	1221 (127)	2001 (369)	1150 (195)	2983 (755)
CO2 emissions factor (g CO2 / kg fuel)[2]	1791 (103)	1930 (103)	1814 (27)	2510 (42)	2717 (74)	1467 (87)
CO emissions factor (g CO / kg fuel)[2]	260 (66)	174 (66)	248 (17)	301 (27)	173 (47)	121 (30)
PM10 emissions factor (mg PM10 / kg fuel)[2]	1700 (1312)	541 (145)	674 (33)	2769 (2428)	139 (81)	38534 (17393)
Average CO/CO2 (ppm CO / ppm CO2)[3]	0.26 (0.08)	0.15 (0.06)	0.22 (0.01)	0.20 (0.03)	0.10 (0.03)	0.13 (0.03)

[1] Cumulative between cold and hot start test phases

[2] Averaged (weighted by fuel consumed) between cold and hot start test phases

[3] Averaged (weighted by time) between cold and hot start test phases

Table 6. Haiti charcoal study results presented using IWA 11 Tier Metrics presented as "AVERAGE (STANDARD DEVIATION) TIER RATING"

Fuel type	**Chabon Vet**			**Wood Charcoal**		**Firewood**
Stove type	Traditional	Improved	Trad + stones	Traditional	Improved	3 stone fire
Number of tests performed	15	2	3	15	3	6
CO emissions (g/MJ$_d$)	55.0 (19.0) TIER 0	22.7 (8.8) TIER 0	42.1 (5.1) TIER 0	83.4 (15.1) TIER 0	28.5 (13.5) TIER 0	52.8 (26.9) TIER 0
PM10 emissions (mg/MJ$_d$)[1]	397 (294) TIER 1	75 (10) TIER 3	129 (7) TIER 3	858 (763) TIER 1	22 (14) TIER 4	16793 (9232) TIER 0
Thermal efficiency (%)	24.2 (5.16) TIER 1	38.0 (1.63) TIER 3	29.2 (3.35) TIER 2	17.8 (3.35) TIER 1	30.3 (4.88) TIER 2	12.0 (3.07) TIER 0
Spec fuel cons (MJ/min/L)[2]	0.072 (0.028) TIER 0	0.041 (0.026) TIER 1	0.057 (0.010) TIER 0	0.101 (0.029) TIER 0	0.074 (0.031) TIER 0	0.158 (0.044) TIER 0
CO indoor emissions (g/min)	1.97 (0.70) TIER 0	0.7 (0.23) TIER 1	1.43 (0.51) TIER 0	2.60 (0.76) TIER 0	1.23 (0.88) TIER 0	2.69 (0.97) TIER 0
PM10 indoor emissions (mg/min)[1]	14.8 (13.1) TIER 2	2.9 (2.4) TIER 3	3.9 (1.1) TIER 3	26.8 (26.7) TIER 1	1.0 (0.8) TIER 4	834 (356) TIER 0

[1] According to the IWA protocol, PM2.5 should be measured. For this study PM10 emissions were measured.

[2] IWA 11 uses this as a metric for low-power (simmer) phase, which was not included in these WBTs, but the metric is still reported

C Influence of user preparation and stove-tending

It was not a primary purpose of this campaign to investigate the influence of specific user behavior on performance and emissions outputs from the WBT. However, this study did seek to incorporate local practice and user behavior in an effort to approach actual use conditions during the WBT. In several of the tests, it is likely that preparation of and user interaction with the stove significantly influenced the WBT outputs reported. These included loading of insufficient fuel to complete the WBT and addition of fresh fuel later to compensate, mechanical agitation and settling of the partially burned fuel and ash, and use of stone or rebar pot supports to elevate the pot off of the burning fuel bed.

To briefly demonstrate the effects of user influence on WBT measurements and outputs, test 04-CV-03 (day 4, Chabon Vet, test #3) will be presented. Figure 12-Figure 15 show the measured timeseries data (water temperature, PM10 mass concentration, gas phase emissions concentration and CO/CO2 ratio) for the hot start phase of WBT 04-CV-03.

Following a relatively long cold-start phase, the hot-start phase progressed for approximately 30 minutes, by which time most other tests were completed. At 30 minutes the user inspected the stove and decided to agitate the fuel bed, removing ash build-up on the surface of the fuel and opening blocked holes in the fuel liner, which are pathways for air entry. The results of this process are a momentary increase in PM10 emissions (Figure 13), a sudden decrease in the CO/CO_2 ratio, and gradual decrease in CO_2 and CO emissions. Following another ten minutes of stagnant temperatures, the user removed the pot and stove from the test platform and proceeded to add new fuel (295 g) to the stove returning the stove to the test platform at approximately 45 minutes. A rapid six-fold increase in PM10 emissions occurred as a result of the new fuel addition. CO_2 and CO levels also rapidly increased, reaching typical high stove output levels. Trace pollutant emissions followed typical trends including early formation of SO_2 and later formation of NO_X upon reaching sufficient stove temperature conditions. An additional increase in PM10 emissions and more rapid increase in gas-phase combustion emissions was recorded at approximately 55 minutes when the user began fanning the stove for one minute to increase aeration of the fuel bed. Shortly thereafter boiling and the end of the WBT were reached.

The test outputs and IWA tier ratings for 04-CV-03 are presented in Table 7. According to the outputs, the stove performance in this test is not significantly different than the average for Chabon Vet in traditional stoves (Table 5 and Table 6) other than the almost double time to complete the WBT. In the IWA framework, this test actually resulted in higher tier ratings than the average, including PM emissions and specific fuel consumption. However, it was evident that the user was less than satisfied with the performance of the fuel-stove combination during 04-CV-03. In addition, this case demonstrates that transient events during the test can have a significant impact on the performance and emissions profile from the stove, but this is not always reflected in the reported test outputs.

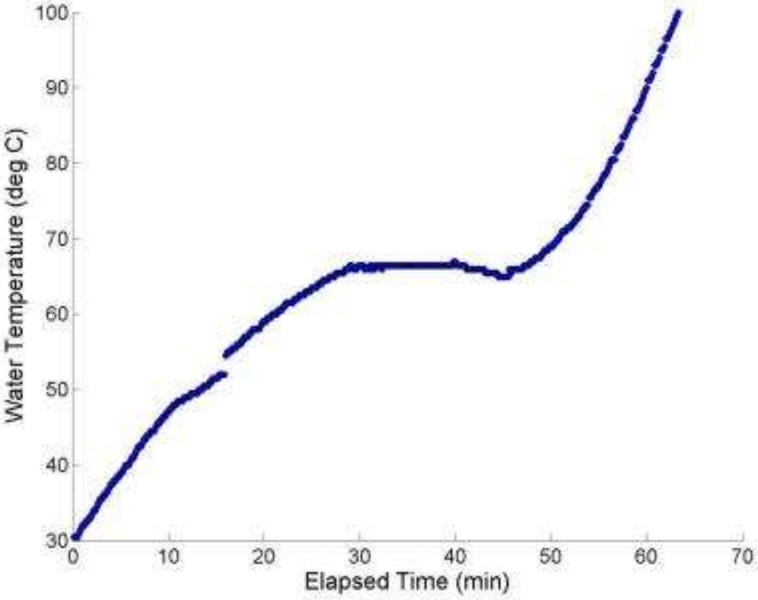

Figure 12. 04-CV-03-HS water temperature

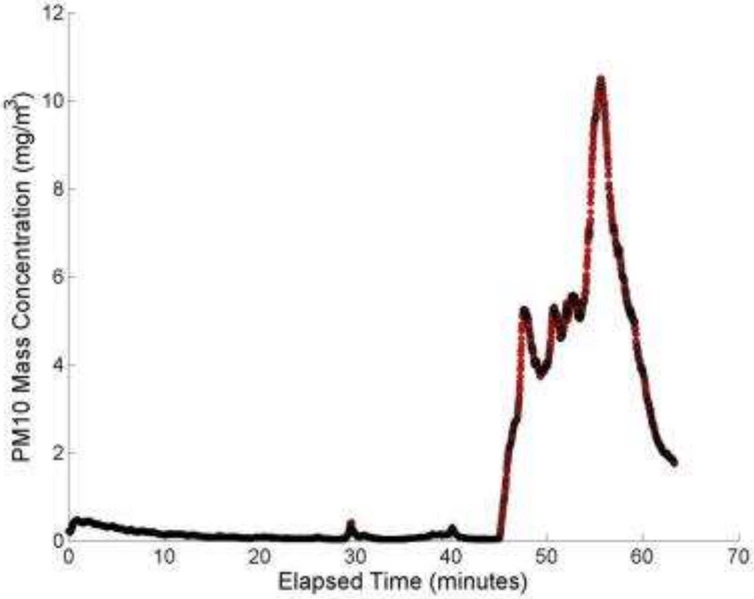

Figure 13. 04-CV-03-HS PM10 mass concentration

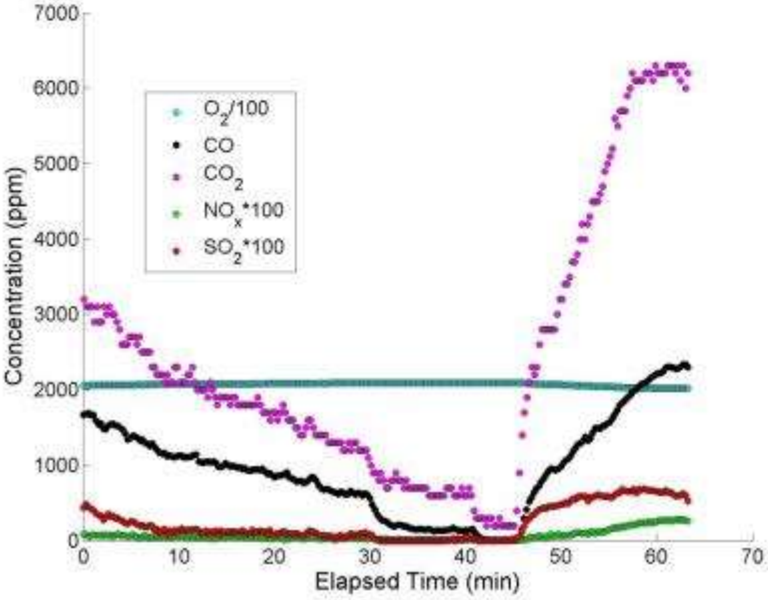

Figure 14. 04-CV-03-HS gas phase emissions concentrations

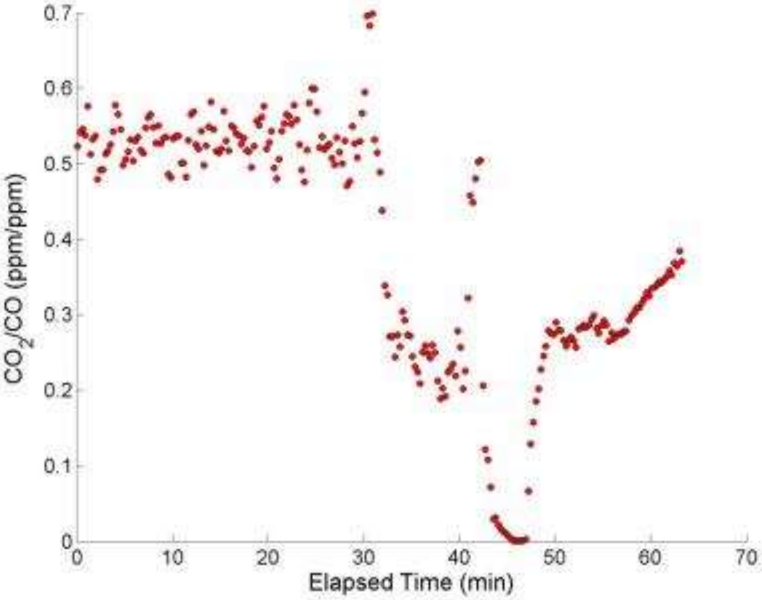

Figure 15. 04-CV-03-HS CO/CO2 ratio

Table 7. Test outputs for 04-CV-03

Fuel type	Chabon Vet		
Stove type	Recho simple (#3 in Table 3)		
Test #	04-CV-03-CS	04-CV-03-HS	04-CV-03
Water boil test phase	Cold start	Hot start	Total/Average
Temp. corrected time to boil (minutes)	28.75	68.34	97.09
Dry fuel consumed (g)	145	195	340
Thermal efficiency (%)	28.1	21.6	23.5
Firepower (kW)	2.0	1.1	1.4
Burn rate (g/min)	5.5	3.1	3.8
Temp. corr'd spec. energy consumption (MJ/L H2O)	1163	1528	1372
CO_2 emissions factor (g CO_2/kg fuel)	1649	1572	1605
CO emissions factor (g CO/kg fuel)	352	402	381
PM10 emissions factor (mg PM10/kg fuel)	992	541	733
Average CO/ CO_2 (ppm CO/ppm CO2)	0.34	0.39	0.38
IWA 11-2012 Metrics (ISO 2012)			
CO emissions (g/MJd)	73.2 (Tier 0)		
PM2.5 emissions (mg/MJd)	134.5 (Tier 3)		
Thermal efficiency (%)	24.4 (Tier 1)		
Specific consumption (MJ/min/L)	0.030 (Tier 2)		
CO indoor emissions (g/min)	1.34 (Tier 0)		
PM2.5 indoor emissions (mg/min)	2.57 (Tier 3)		

D Discussion of error and uncertainty

Many efforts were taken during this study to minimize error; however, emphasis was intentionally not placed on minimizing uncertainty in the results. All measurement instruments were within their factory calibration periods throughout the campaign, and several zero calibrations were performed on the PM10 analyzer throughout the study. Background levels of emissions were measured before and after each test and subtracted from the measured values during the WBT. However, there may have been variation in background levels during the test, especially CO_2 and PM10 due to other combustion activities occurring in the area around the test site.

All successful tests performed during the study complied with the modified WBT procedure outlined earlier in this report. These tests differed from the WBT protocol in that they emphasized operation of the stove by the user according to their normal cooking behaviors. Additionally, a goal of this study was to include a variety of stove types, ignition methods and cooking settings, again emphasizing the user's preference, familiarity and comfort. Much uncertainty and uncontrollability arises from allowing freedom and variation in stove operation during the WBT. However, the intent of this study was to include a sufficient number of tests with each user and location to obtain a statistically significant average per household, and a sufficient number of tests through the entire campaign to obtain a representative variety of common practice and resulting variation in test outputs. Although in some cases, for example tests using Chabon Vet in improved cook stoves, the number of successful WBTs is likely insufficient to obtain accurate average performance and emissions outputs.

E Discussion of challenges

Field testing is susceptible to a variety of challenges ranging from equipment failures to communication barriers. Overall, the field team was able to overcome many of the urgent problems that were encountered with few setbacks. The mobile lab consists of many individual parts and some of those are susceptible to failure, especially in the hot and humid outdoor conditions at the typical Haitian home. In addition, daily unpacking and packing of the mobile lab increases the risk of malfunction or failure. Equipment malfunctions caused minor delays in testing on a couple of occasions. One involved the failure of the extraction blower in the emissions collection system. Luckily the field team was prepared with backups of the mobile lab's major components, so in this case, the blower was replaced. Another challenge involved the battery system in the electrochemical gas analyzer, which unexpectedly stopped charging on day five of the campaign. The field team was prepared with adequate knowledge of the system and the right tools and materials to implement a solution.

A challenge that was largely overlooked prior to the campaign was the difficulty in communicating with users at each household. In many cases, the household members may have been overwhelmed or intimidated with the unfamiliar and large apparatus constructed in their kitchen and, therefore, tended to either look on with curiosity from a distance, or continue along with their daily activities paying little attention to the testing effort. The local support team from CRI was good about informing each household with regards to the purpose of the testing and the need for user participation in the testing. However, since the support team sometimes needed to tend to other business, the testing team was periodically left alone with the user and insufficient communication ability between the two caused confusion, for example as to who's role it was to tend to the stove between the cold and hot start test phases. In most cases this did not likely have a major impact on the outcome of the test since charcoal stoves usually require little effort to operate after igniting the fuel.

IV Conclusions and recommendations

The aim of this study was to perform rigorous field evaluations of an alternative, locally-produced cooking fuel (Chabon Vet) and commonly used wood-derived fuels (wood charcoal and firewood) in actual use conditions with user participation. A mobile laboratory apparatus was designed and deployed by a research team from MIT's D-Lab to perform the evaluation in and around Cap-Haïtien, Haiti. A modified version of the standard laboratory test method for cooking technology, the WBT, was performed during the evaluations. The field team set up the mobile lab at a different household each day and worked with stove users to perform the tests. This method is unique in that it utilizes advanced measurement methods commonly used in controlled laboratory testing but brings the laboratory to the home and involves the user to incorporate local practice and behavior. Users performed cooking tasks according to their normal practice, but within the bounds of the WBT. Triplicate WBTs for each fuel type were performed each day to attempt to achieve statistically significant results. Test data was analyzed using a workflow developed at D-Lab, producing test outputs detailed in the WBT and IWA 11-2012 framework.

A total of 57 individual WBTs were performed at seven different household locations and one commercial location. Of the 57 WBTs performed, 44 were completed successfully (77% success rate). Three different fuels (Chabon Vet, wood charcoal and firewood) and eight different stoves separated into four different categories (traditional unimproved, traditional unimproved with pot supports, improved, and three stone fire) were tested.

The aggregated and averaged test outputs show that in general Chabon Vet performs similarly to conventional wood charcoal in terms of practical use, efficiency and emissions. Use of Chabon Vet in both traditional and improved stoves requires more time to complete the WBT compared to wood charcoal due in large part to its lower net calorific value. The average burn rate and firepower of stoves using Chabon Vet are 30-45% lower than stove using wood charcoal, resulting in more efficient heat transfer from the burning fuel to the pot. The average dry fuel consumed during the WBT was almost identical for Chabon Vet and wood charcoal.

In terms of emissions, this study has reaffirmed previous findings which show that the use of carbonized fuels results in significantly lower respirable particulate (PM10) emissions compared to firewood, a 2-3 order of magnitude difference in this case. Emissions factors of CO_2 (g CO_2/kg fuel) from Chabon Vet use are on average 29% lower than wood charcoal, which is likely attributable to its lower carbon content. CO emissions factors for both Chabon Vet and wood charcoal are significantly higher than for firewood in a three-stone fire.

Within the IWA 11 framework, Chabon Vet performed slightly better than wood charcoal within the same stove category. Overall, Chabon Vet used in improved cook stoves exhibited the highest tier ratings of all fuel-stove combinations tested. In particular, carbonized fuels demonstrated high tier rankings (Tier 3 or 4) in PM10 emission factor, PM10 indoor emissions and thermal efficiency. Chabon Vet and wood charcoal both rated Tier 0 or 1 in CO emissions factor, CO indoor emissions and specific fuel consumption (energy consumption normalized by test time and water volume).

Standard deviations of many of the Chabon Vet test outputs are higher than for wood charcoal or firewood, indicating more variation in performance, which could be attributable to variation in the briquettes themselves or, more likely, user unfamiliarity with the product. One significant difference between the fuels tested is their calorific value, which for Chabon Vet is 25% lower than wood charcoal. The high ash content of Chabon Vet is a contributor to the comparatively low calorific value and is likley a reason for the higher CO emissions from Chabon Vet.

The use of improved, insulated stoves was shown to make a significant impact on stove performance and emissions. Thermal efficiency increased by 60-70% and fuel consumption decreased by 40% for both Chabon Vet and wood charcoal in an improved stove compared to traditional stove. CO emissions factor decreased by 33-43% and PM10 emissions factor decreased by 68-95% for both Chabon Vet and wood charcoal in an improved stove. Significant health, environmental and livelihood benefits can be gained by using Chabon Vet coupled with improved cook stoves.

A priority area for future work on alternative carbonized fuels should be addressing the heat output, which could be a significant practical shortcoming of briquette fuels. However, it should be better understood what the user requirements are in terms of heat output and cooking time. If users are generally less concerned, or can adapt to a fuel that produces less heat but a more prolonged burn then it won't be necessary to alter current carbonized briquette fuels. Performing follow-on Kitchen Performance Tests (Bailis 2007), Controlled Cooking Tests (Bailis 2004) and/or user interviews could provide useful supplemental information to these tests regarding user behavior and perception of conventional and alternative fuels. In addition, efforts need to be made to ensure more complete combustion of carbonized fuels in natural draft stoves. It is likely that part of the solution lies in reducing or ensuring better removal of ash, and part of the solution lies in stove designs which supply sufficient air at the correct location in the stove to oxidize CO and other products of incomplete combustion. Finally, this study identified a strong correlation between fuel type and stove efficiency and emissions. Further investigation should be undertaken to determine the fuel characteristics that influence where a given fuel falls on the spectrum of emissions and efficiency performance, and perhaps more importantly, user centered outputs such as time and fuel required to complete a cooking task.

V Acknowledgements

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Figure 16. The D-Lab research team and staff members from Carbon Roots International at their production facility near Cap Haïtien, Haiti

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