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Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa

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ABSTRACT

This paper presents the results of two studies conducted to evaluate the performance and usability of household biomass cookstoves under field conditions in rural sub-Saharan Africa. Cooking tests and qualitative surveys compared improved, manufactured stove models based on the 'rocket' design with the traditional three-stone fire. All tests and interviews took place in household kitchens in two village areas in Western Uganda and Western Tanzania. The performance parameters evaluated in cooking tests were specific fuelwood consumption and cooking time. Surveying of household cooks gathered information about prevailing cooking practices, stove preference and usability, and willingness to pay for novel stove types. Test results showed that the manufactured stoves, in general, yield a substantial reduction in specific fuelwood consumption relative to the three-stone fire, with results varying by stove type and type of food cooked. Survey data suggests that while cooks recognize fuelwood savings as an important benefit, overall stove preference depends upon a combination of this and other factors, including cooking time, stove size and ease of use. These findings highlight the importance of testing multiple cookstoves for preparation of a variety of food items, as well as combined use of quantitative stove tests in combination with qualitative surveys in efforts to determine suitability of cookstoves for household use in a given community.

Background

Roughly half of the world's population burns solid biomass fuels for cooking and heating needs. Throughout poor, rural areas of sub-Saharan Africa, biomass is the dominant fuel, and cooking is usually performed using a simple three-stone fire or "open fire" (see Fig. 1). Particularly in high-altitude areas, where nighttime temperatures are colder, cooking is often performed in poorly ventilated structures. Incomplete combustion of these fuels and poor ventilation result in high indoor concentrations of health-damaging pollutants including particulate matter and carbon monoxide (Jetter and Kariher, 2009; Rehfuess, 2006). In addition, especially in regions where biomass is scarce, time and effort spent gathering firewood can be a substantial burden on households, particularly children and women (Rehfuess et al., 2006).

The cookstove study described here was undertaken as part of the Millennium Villages Project (MVP), a multi-sectoral development project spanning 14 sites in 10 countries throughout sub-Saharan Africa. The MVP supports interventions in areas of agriculture, health, education, infrastructure and environment, conducted as a partnership among the Earth Institute at Columbia University, Millennium Promise, the United Nations Development Programme (UNDP) and local MVP site teams, in cooperation with domestic governments and other local partners (Sanchez et al, 2007). One component of the MVP's work in the area infrastructure and energy consists of testing and introduction of improved biomass cookstoves. Two stove research efforts were carried out in MVP village areas in Uganda and Tanzania in 2009.

Efforts to design, build and promote improved stoves have been undertaken in many communities throughout the world in recent decades resulting in the development of a wide variety of stove types employing a range of materials, design features and production processes. Some stove models are made by local artisans in or near the home using locally-available materials such as mud, dried grasses and anthill/termite soil. These artisanal stoves may also include factory-produced elements which are often made elsewhere and transported to villages, such as high-temperature bricks, liners made of fired clay, or metal fuel shelves. Other models, referred to here as "manufactured" stoves, are produced entirely in factories, either domestic or international, then transported to villages as a finished product (MacCarty et al., 2010).

Despite years of research, not all stove programs are supported by careful performance and user preference studies, and stove programs have sometimes resulted in introduction of models that underperform

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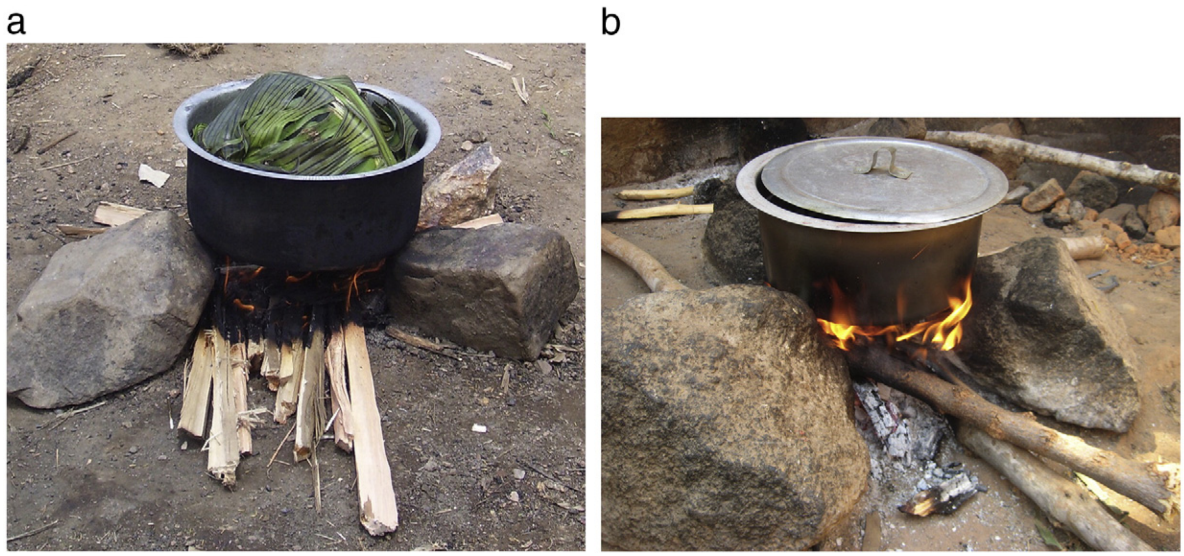

Fig. 1. (a and b): (L to R) Three-stone fires in Uganda and Tanzania.

relative to the three-stone fire (Quadir et al., 1995; Wallmo and Jacobson, 1997). For this reason, it is important that stoves are tested prior to implementation to ensure that the new design provides a significant improvement, given the prevailing cooking practices. While laboratory testing is a helpful guide, stoves need to be evaluated in field conditions as well. Moreover, because an improved stove offers no benefit if it is not adopted and used regularly, the study investigated stove preference and usability, primarily through a survey which asked about factors such as cooks' willingness to pay for the stoves as well as perceptions of their suitability for typical household cooking. To these ends, the following study includes both a technical portion, which investigates fuel consumption and cooking time, and a user survey, probing a mix of qualitative and quantitative issues related to stove acceptability.

The cookstoves tested in this study are manufactured models, based on the "rocket" design, developed at the Aprovecho Research Center (USA), which generally includes the following features: a vertical, L-shaped, insulated combustion chamber (forming an internal chimney); a metal grate which supports fuelwood above the floor of the combustion chamber to increase airflow; a metal pot rest at the top of the stove; and metal cladding surrounding the stove body (see Fig. 2.2, item "9. Metal Skirted Rocket" in MacCarty et al., 2010). These stoves may also employ a metal cylindrical "pot skirt" on the top of the stove to force the hot combustion gases close to the sides of the saucepan. These features are intended to improve combustion and airflow while increasing heat transfer to the pot, with the aim of improving stove efficiency and reducing pollutant emissions. (Winiarski, 2005) The Uganda and Tanzania MVP studies included a variety of locally-produced and imported stoves which employed "rocket" design elements to varying degrees.

General approach and methodology (both study areas)

Preparation for testing (household selection, preliminary surveys and stove delivery)

Thirty households were randomly selected from each of the MVP databases of 300 households for the Uganda and Tanzania project sites. MVP staff visited each household to identify the primary cook (usually the wife or eldest daughter of the head of household), to describe the study and enlist cooks' cooperation, and to conduct a preliminary survey to gather basic and essential information, including: the food cooked most often (usually a starch), the amount cooked in a typical meal, the typical cooking duration, the approximate amount of fuelwood consumed, and the dimensions of the pot used most often for cooking this food. Data from this preliminary survey was used largely for planning subsequent steps of the study. For example, data on types and quantities of the food most commonly cooked, as well as measurements of pots, were used by MVP staff to purchase supplies for future visits to households for testing. Following the preliminary survey, the manufactured stoves were delivered to the households one to four weeks before testing to allow time for cooks to become familiar with their use.

There were two important differences in preparations for the two study areas. One was that, while both the Uganda and Tanzania studies investigated the food cooked most often, the Tanzania program also tested the food that required the longest cooking time. Second, the types of improved stoves tested were different for the two sites due to differing availability of both locally-made and imported manufactured stoves at the time of each study. The three-stone fire was the dominant traditional cooking method used for comparison in both locations.

Stove testing protocol

Technical aspects of stove performance were evaluated using a modified version of the Controlled Cooking Test (CCT) protocol developed by the University of California-Berkeley and Shell Foundation Household Energy and Health Projects (Bailis, 2004). The typical CCT measures fuel consumption of stoves in a laboratory or standard structure where a local cook performs a common local cooking task, and the food and wood are provided. For this study, the CCT was modified such that all tests were performed by household cooks in their own rural kitchens using fuelwood obtained by households, with food provided by the MVP. The following comments apply to all tests, except where differences are noted by study location.

- *Number and grouping of tests*: For all cooking tests, all stoves, including the three-stone fire, were tested simultaneously, except when food required close supervision, in which case the batches were cooked consecutively, in random order, on the same day. Both the simultaneous and consecutive tests are referred to as "triplet" tests for the Uganda study and "quadruplet" tests for the Tanzania study, since 3 and 4 stoves were tested together in each area, respectively. Each test was conducted twice in each household for a total of 60 sets of tests in each study area.

- *Food quantity*: The amount of food cooked on each stove was representative of the quantity prepared for a normal household meal. This differed by household, but was consistent for all stoves in a single test. MVP provided the food used for cooking since collection of multiple extra batches of food would place a severe burden on many households.
- *Fuelwood*: Fuelwood was collected by households from local sources. While wood type, quality, and moisture content varied from by household and by day, the same mix of wood was used on all stoves in each test.
- *Testers*: MVP staff enumerators observed cooking and took measurements during the cooking tests. They were native to the region, spoke the local language and were trained together to ensure consistency of procedures.
- *Equipment*: MVP provided multiple pots similar to those normally used by each household. A digital Salter Brecknell hanging scale with 10 kg capacity and 10 g resolution was used for weighing the fuelwood and food. A plastic bucket was used to hang items from the scale. A measuring cup was used to measure the quantities of water.
- *Procedure*: Before each test enumerators measured and set aside, for each stove, both the amount of dry food and fuelwood to be used and recorded these weights. Enumerators also recorded the pot dimensions, type of fuelwood, weather conditions, and test location. Cooks started the fires with twigs and grass (this weight was not measured). Enumerators recorded the time at key cooking stages: when the fire was lit, when the pot was placed on the fire, and when cooking was finished. Household cooks conducted all cooking tasks. Water was not used to extinguish the wood. After cooking, enumerators recorded the weights of fuelwood remaining and of the cooked food for each stove, then calculated cooking duration and the fuelwood consumption by difference.
- *Metrics*: Specific fuel consumption (SFC) was defined for this study as the ratio of the quantity of fuelwood consumed during cooking (kg) over the quantity of food cooked (kg dry weight, before cooking). This value is dimensionless. The duration of cooking (min) was also used.

Survey of cooking practices and stove preferences

In addition to the preliminary questionnaire, enumerators administered a more detailed survey of cooking practices and cooks' views regarding the stoves being tested. This survey was administered during the second day of cooking tests. The respondent for each household was the primary cook.

One set of survey questions related to the cooks' overall impression of the stoves' design, usability and cost, with the general objective of determining which stoves, if any, cooks would purchase.

- *Stove ranking*: It is important to understand if a stove is preferable not only to the three-stone fire, but also relative to other manufactured stoves, both imported and locally-made. Cooks were asked to rank all stoves tested, including the three-stone fire, in order of preference, and provide up to three reasons for the ranking of each.
- *Evaluation of each stove type*: A variety of questions were asked to probe cooks' views of each stove including: what aspects the cook liked and disliked for each stove (up to three responses for each); whether the stove was the proper size for cooking most meals; and whether the cook would use each stove generally or only for specific foods.
- *Time/effort for tending*: Because cooking can occupy hours each day and is often intermingled with other tasks such as childcare and housework, the need to tend a fire is a key factor in convenience of a given stove. The survey asked both if each stove required more or less tending than a three-stone fire, and whether this was a problem for cooks.
- *Willingness to pay*: Production of a stove that performs well and remains affordable for the target market has been a major challenge. Cooks were asked whether they would purchase the improved stoves at three prices representing a) 0–25% subsidy, b) roughly 50% subsidy, and c) roughly 65–70% subsidy.

Other questions investigated the cooking practices and equipment before the introduction of manufactured stoves, as well as the patterns of using multiple stoves might change after adoption of at least one manufactured stove. Together, these are intended to probe, among other questions, whether more than one improved stove may be needed in each household kitchen to fully replace the three-stone fire and ensure the intended benefits.

- *Pot size*: Matching stove and pot sizes is essential for usability, and though the size of the three-stone fire can be adjusted to fit a wide

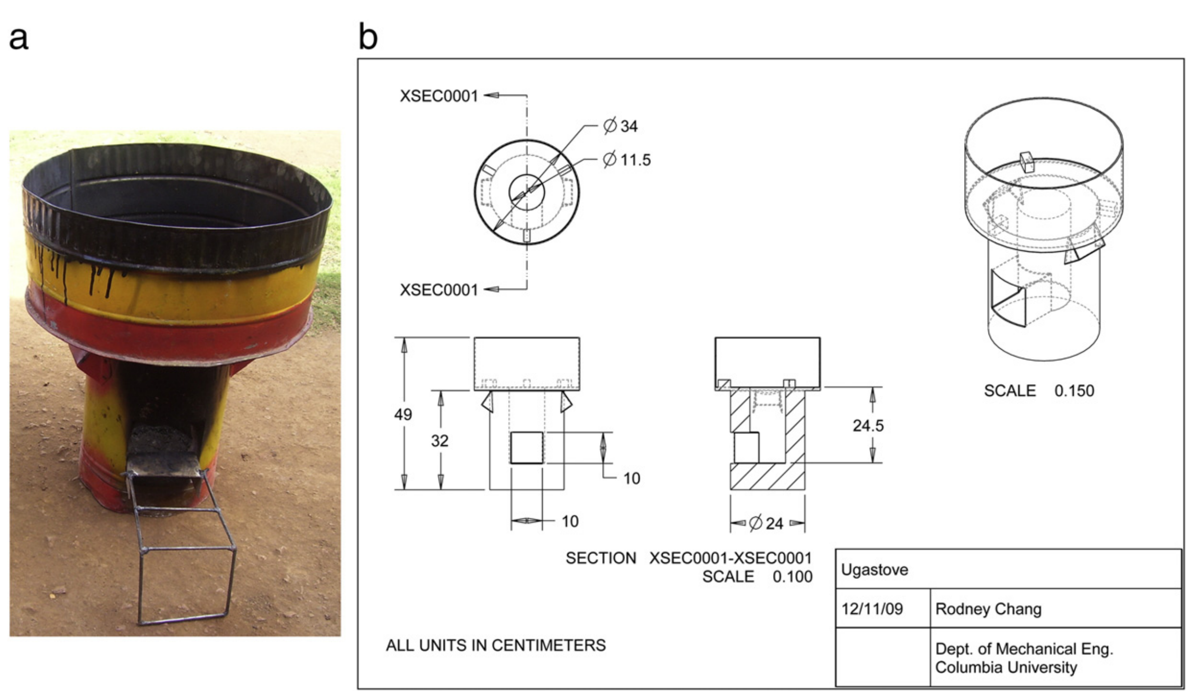

Fig. 2. (a and b): Photo (left) and drawing (right) of the Ugastove (manufactured in Uganda).

range of pots, most manufactured stoves are of a fixed size. Cooks were asked to show the three pots they use most often for cooking, and the diameters of these were measured.
- *Cooking with multiple fires*: If cooks typically use more than one fire for the same meal, this suggests that some use of three-stone fire may continue even after adoption of one or more improved stoves. Cooks were asked how many separate fires they typically cook with simultaneously for each meal, as well as how many total hours they spend cooking each day and how many of those hours include cooking on two or more fires at once.
- *Effect of ownership of manufactured stove(s) on use of three-stone fire*: Cooks were asked whether they would still use the three-stone fire for some tasks even if they owned one or two improved stoves. Such tasks might include preparation of multiple dishes at once, use of pots that do not fit the improved stove, or cooking for visitors or other special occasions.

Procedures and results for each study area

Ruhiira village, Uganda

The geographic focus of the first set of stove tests was an MVP study area surrounding Ruhiira village, near Mbarara, in the Isingiro District of southwestern Uganda, at an elevation of approximately 1500 m. Fuelwood in Ruhiira is extremely scarce; clearing of forests to open land for cropping is estimated to have left about 5% of the land with tree cover (National Forest Authority of Uganda, 2007). As a result there is a serious shortage of fuelwood. A survey of 300 households conducted in 2007 showed that 99% of cooking was done with fuelwood and crop residue, and that 95% of fuelwood consumed is collected while the remainder is purchased.

Stoves tested

In the Ugandan “triplet” tests, two cookstoves, both modeled on the ‘rocket’ design, were tested alongside the three-stone fire.

Ugastove. The Ugastove (formerly called the UCODEA stove) is a metal and clay stove (see Fig. 2) manufactured in a factory in Kampala by the Uganda Stove Manufactures. A ceramic liner encased in sheet metal forms the L-shaped combustion chamber characteristic of the rocket stove design. The Ugastove also has a metal “pot skirt” permanently fixed to the outer edge of the top of the stove. The Ugastove is manufactured in several sizes. For testing, the stove model with a 34 cm diameter top and pot skirt was used. This stove weighs 13 kg.

StoveTec. The StoveTec stove is a metal rocket stove designed by Aprovecho Research Center (USA), and manufactured in China (see Fig. 3). The combustion chamber is made of a lightweight, insulating refractory ceramic encased in steel. The StoveTec stove comes with a removable, adjustable pot skirt. StoveTec stoves are produced in a range of sizes and with one or two doors. The single-door, 26 cm diameter stove with a weight of 7.3 kg was used for this testing procedure.

Selected foods and cooking tasks

The standard cooking task selected for the CCT at the Ugandan site was steaming plantains to prepare a local staple known as “matooke” (see Fig. 4). First the bottom of the saucepan is filled with banana stems to create a space for water to be added, out of contact with the plantains. Next, the plantains are peeled and wrapped in banana leaves and placed in the saucepan. The plantains are then steamed until soft. Cooks test the plantains consistency by hand to determine when cooking is complete, remove the pot from the fire, and mash the plantains, also by hand.

Cooking test results

Fig. 5a shows the SFC measurements, with 95% confidence intervals, of the Ugandan cooking tests. Fig. 5b shows the percentage fuel savings for each stove, relative to the three-stone fire. Both stoves show substantial and statistically significant fuel savings relative to the three-stone fire, defined as the percentage difference between the SFC values of each improved stove relative to the three-stone fire. The Ugastove stove showed fuelwood savings of 46%, and the StoveTec showed fuelwood savings of 38%. In a region where fuel scarcity is a serious problem, fuelwood savings of 38 to 46% can have a large impact.

Fig. 6 shows the SFC versus the weight of food for each stove test. The weight of the batches of food ranged from 1 to 6 kg, and averaged 3.2 kg. The figure shows that, over this range, the three-stone fire uses more fuel on average than both of the two

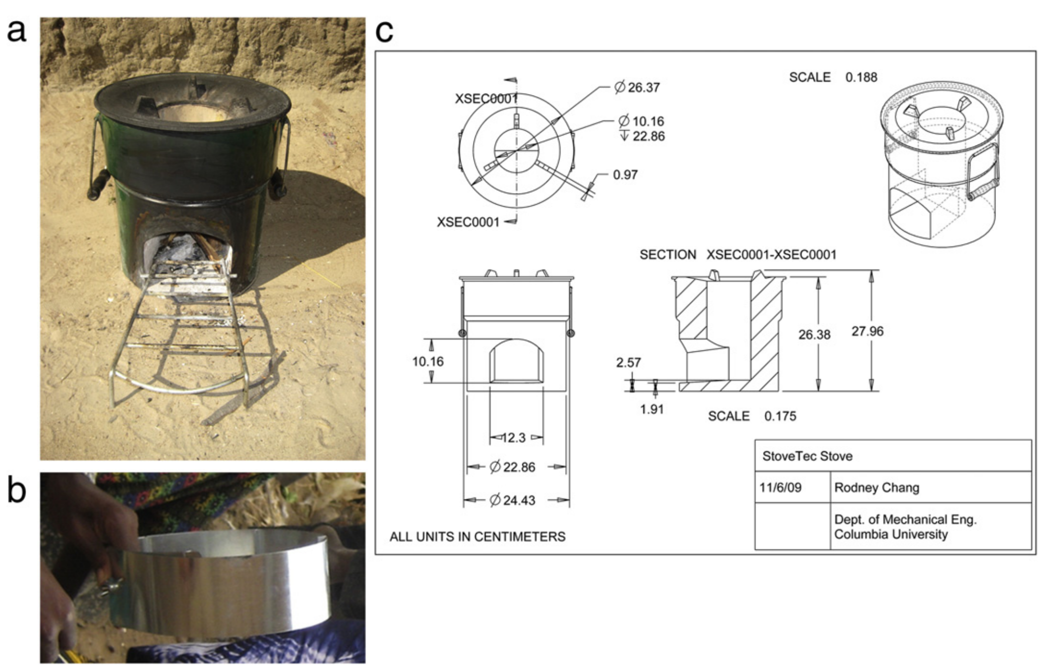

Fig. 3. (a, b, and c): Photos of StoveTec (top left) and pot skirt (bottom left) and drawing (right) of the StoveTec stove (manufactured in China).

Fig. 4. (a, b, and c): Preparation of matooke (plantains) for steaming (Ruhiira, Uganda).

manufactured stoves. The trend shown in this graph of declining fuel consumption per unit of food cooked as batch size increases suggests that, for all stoves, fuel efficiency and heat transfer tend to improve as the scale of cooking increases. For this reason, the SFC of large institutional stoves is, all other factors being equal, expected to be lower than that of household stoves.

The second key technical metric measured was cooking time. The three-stone fire required approximately 17 min to cook matooke. The Ugastove showed a statistically significant increase in cooking time of 27% over the 3-stone fire (22 min), whereas the StoveTec stove showed only a slight increase (18 min, or an additional 5%) which was not statistically significant.

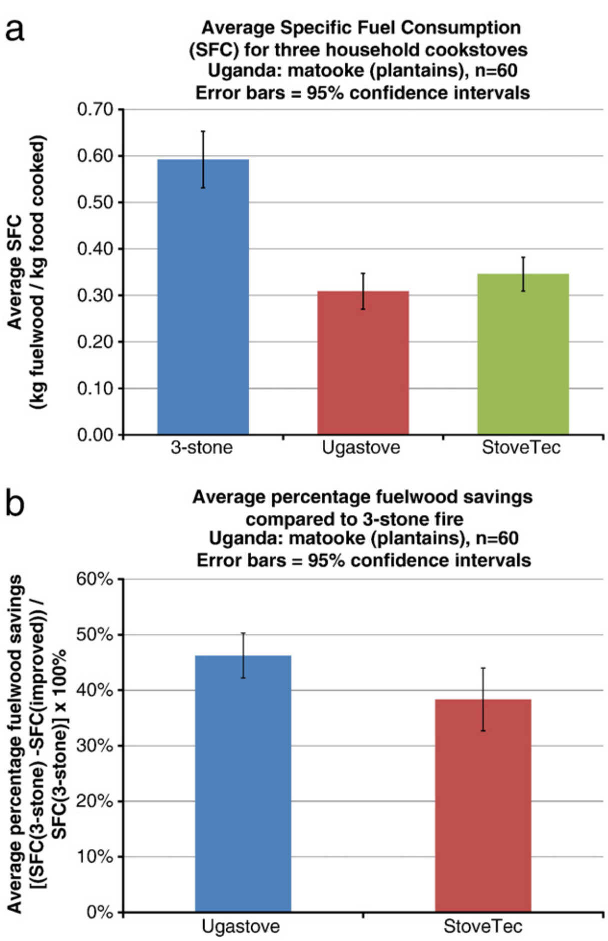

Fig. 5. (a and b): Uganda "triplet" CCT results: (L to R) a) SFC values for two manufactured stoves compared to the three-stone fire; b) percentage fuelwood savings derived from SFC differences.

Fig. 7 is a graph of the specific fuel consumption for the stoves versus cooking time. For both stoves there is no clear trend in SFC values with cooking time. This is to be expected since only one food (plantains) was cooked in the Ugandan study, thus limiting the durations of each cooking test to a fairly narrow range. Tests including more than one food type (such as those conducted in Tanzania, discussed later) show a wider range of cooking times and a more pronounced change in SFC with duration.

Survey results

The Uganda study also included a detailed survey which was administered in 24 household kitchens.

The results of stove ranking are shown in Fig. 8. The cooks overwhelmingly preferred the StoveTec stove, with 23 of 24 respondents ranking it first. Over half ranked the Ugastove second, but 42% ranked the Ugastove last, meaning that they preferred the three-stone fire. That is, although the Ugastove showed the lowest fuel consumption overall, other unfavorable aspects prevailed in nearly half of users' assessments. This disparity between fuel savings and acceptability strongly recommends inclusion of a qualitative evaluation alongside fuel consumption tests in stove assessment efforts.

Cooks were asked to list three things they liked and disliked about each stove. The responses are shown in Figs. 9 and 10. The most widely reported favorable trait (over 90% of cooks) was that both stoves save wood. The StoveTec was noted almost universally as cooking quickly while the Ugastove was favorably rated primarily for reduced smoke and reduced soot and dust, though measurements of emissions were beyond the scope of this study. In identifying unfavorable traits, around 40% of the cooks found both stoves difficult

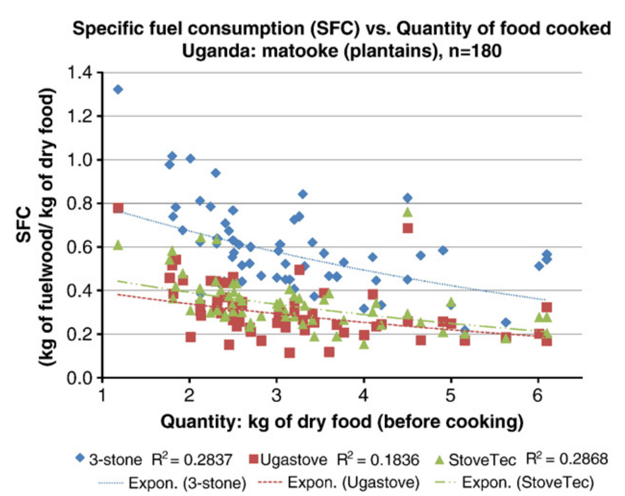

Fig. 6. Fuel consumption trends with mass of food cooked (plantains, Uganda).

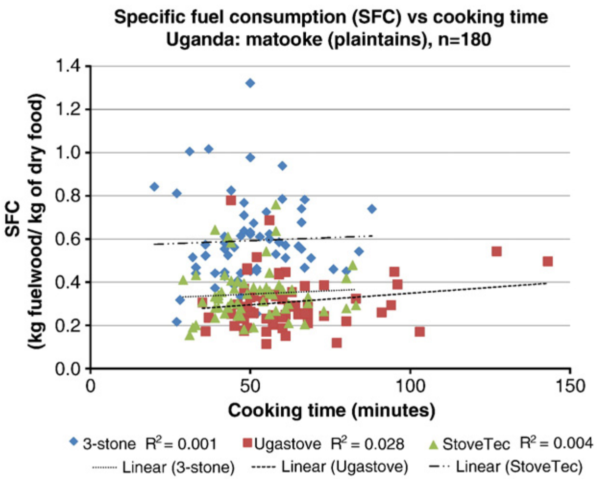

Fig. 7. Fuel consumption trends with cooking time for three stoves (Uganda).

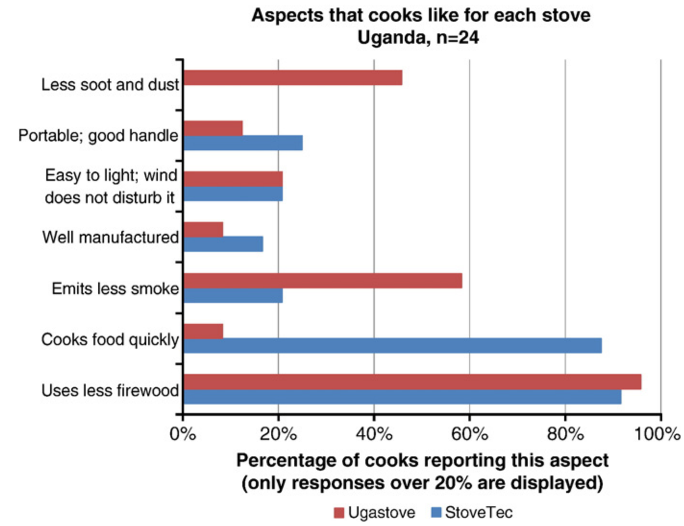

Fig. 9. Aspects that cooks liked for each stove (Uganda).

to light. The main user complaint with the Ugastove (over 80%) was the large increase in cooking time, a difference which was confirmed with technical measurements. Other unfavorable traits included the tendency of the metal shell of the Ugastove to become hot to the touch, making cooking difficult, as well as the Ugastove's bulky, tall, and top heavy design. Complaints about the StoveTec were fewer and limited in scope. About 29% of StoveTec users found it unstable and easy to tip over, but 42% of respondents did not have any complaint about the StoveTec stove.

When cooks were asked whether additional tending was required for each stove and whether this presented a problem, responses broadly favored the StoveTec. For the Ugastove, 46% of respondents stated that it required more tending and that this interfered with other activities (compared with 17% for the StoveTec). In contrast, 38% of respondents said the StoveTec required more tending but that this was not a problem (compared with 8% for the Ugastove). Cooks explained that, although the StoveTec does require more tending, it cooks quickly and thus saves time overall. The Ugastove, however, not only required constant tending (the fire easily went out and wood had to be constantly added since the small fuel opening restricted the amount of wood inserted at a given time) and also had a longer cooking time.

Fig. 11 shows a histogram of the most frequently used pot sizes with indications of the diameter of key stove features. The average pot diameter is only slightly wider than the StoveTec top, but substantially smaller than the diameter of the Ugastove. When asked whether each stove is properly sized for cooking most meals, 92% of respondents felt the StoveTec stove was the right size, however, less than half thought the Ugastove was the appropriate size. Although the smaller of two Ugastove models was used for this study, 25% of respondents said it was too big. Another 17% reported that it was improperly sized for their household's saucepans.

While both stoves include a pot skirt, the fact that the StoveTec's is adjustable in size and removable while the Ugastove's is fixed likely contributes to the disparity in reported usability. Although the StoveTec's pot skirt allows a maximum saucepan diameter of 23 cm, which is smaller than the majority of pots used in the study area, this did not impact cooks' behavior since all cooks simply removed the pot skirt during testing. In contrast, the Ugastove's larger, fixed pot skirt garnered many complaints, including that the Ugastove was too tall (25%), placed a hot surface near the pot (33%) and that it caused a smoky flavor in the food when a smaller pot was used. Overall, while details may require more investigation, results here suggest that while a pot skirt can offer an improvement in fuel consumption it may compromise overall utility for the cook in ways that lead most to simply avoid its use if possible.

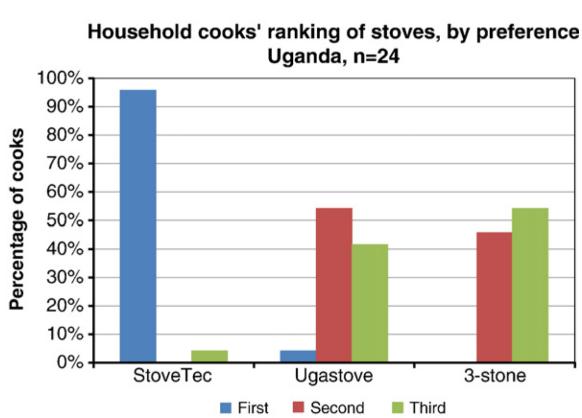

Fig. 8. Rank of preference for each stove (Uganda).

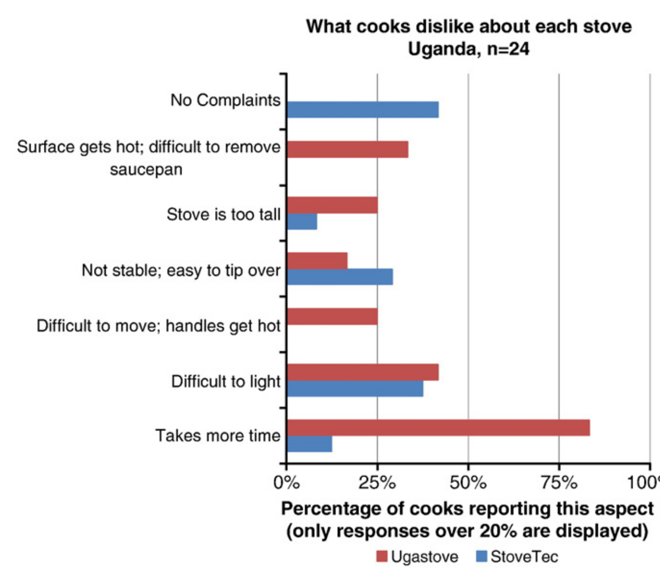

Fig. 10. Aspects that cooks disliked for each stove (Uganda).

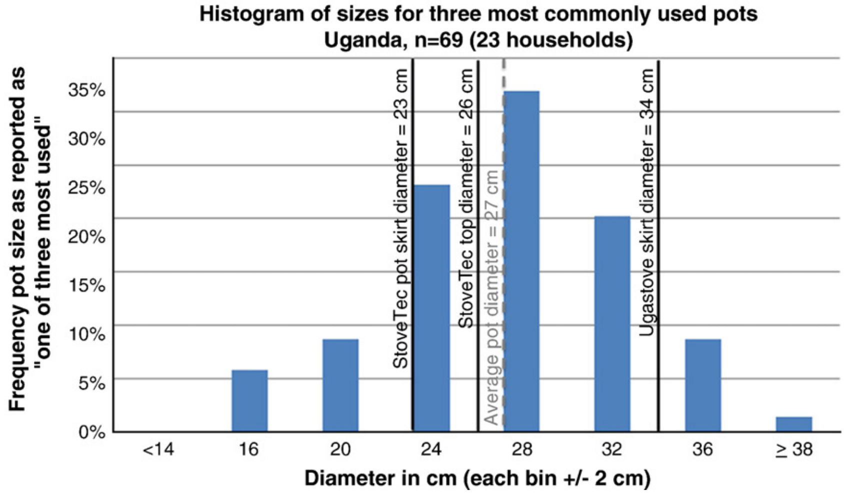

Fig. 11. Size comparison of stoves and commonly used pots (Uganda).

The StoveTec costs roughly $7–8 at the factory in China, and bulk sea freight to Africa, import duties and taxes, ground transportation to Ruhiira and retail markup are expected to add about $10–15. The Ugastove costs $12.50 in Kampala; overland transport to Ruhiira (about $3–4 per stove) and wholesale and retail markups (each of about 15%) would add a total of perhaps $7 per stove. Thus the estimated retail price for both stoves in Ruhiira village could range from $17 to 24, with a conservative estimate of $20–22. The cooks in the Uganda study were asked if they would purchase the improved stoves at three possible prices and the results are shown in Fig. 12. At all prices proposed, more cooks expressed willingness to purchase the StoveTec than the Ugastove. At $10, a predicted price under a subsidy scheme, almost 60% of people said they would purchase the StoveTec, compared with 40% for the Ugastove.

In summary, although cooking tests showed a slightly larger fuel savings to be gained by use of the Ugastove, the StoveTec stove was preferred by a large majority of cooks. Cooks' dislike of the Ugastove appears to be due to a combination of the stove's slower cooking time, inconvenient size, fixed pot skirt, and other design features.

Discussion of results from Ruhiira, Uganda

Other tests have been conducted with these stoves, both in laboratory and field conditions, allowing comparison with the Ruhiira results.

The U.S. Environmental Protection Agency (EPA) studied several stoves, including the Ugastove, using a Water Boiling Test (WBT), a standard laboratory protocol used to analyze fuel consumption parameters during different boiling and simmering phases. This study found that the Ugastove's SFC was about equal to the three-stone fire in two boiling tests, but higher in the "simmer" stage (Jetter and Kariher, 2009). The disparity between the EPA and MVP results suggests that the laboratory WBT is not necessarily predictive of stove performance in household kitchens. At least two other studies conducted in India and Mexico (Smith et al., 2007; Berrueta et al. 2008) also found the WBT to be a poor predictor of fuel consumption in the field.

The Center for Entrepreneurship in International Health and Development (CEIHD) conducted a fuel use study on behalf of the Uganda Stove Manufacturers, the makers of the Ugastove (Haigler et al., 2007). This study employed the Kitchen Performance Test (KPT) which measures the total fuel consumption for all household cooking every 24 h period for one week in each home that has an improved stove. The KPT found 58% fuel savings with the Ugastove which is roughly comparable with the MVP's Ruhiira CCT results (46%), though the relative magnitude of the findings for these two tests is the reverse of what one might expect. Surveys indicate that Ruhiira households tend to use more than one stove during each day's cooking, and households possessing only one improved stove would presumably perform the remainder with a three-stone fire. Therefore, since a KPT averages fuel consumption across all stoves, one would expect it to show less fuel savings than a CCT, which directly compares an improved stove and a three-stone fire for the same cooking process. Some possible explanations include: the small sample size of the KPT study – 13 households compared to 60 in the CCT – leads to higher statistical uncertainty in the CEIHD results. Also, participants in the CEIHD study may have been instructed to avoid use of the three-stone fire. In addition, in the KPT, households are left largely unsupervised between weighing sessions which may result in measurement error due to improper use of wood that has not been weighed.

The StoveTec stove has also been tested in multiple studies, primarily by the Aprovecho Research Center, the designers of the StoveTec stove and a leading institution in biomass stove design and testing. An Aprovecho CCT study measured fuel savings of 29% in the laboratory and 41% in the field – a test hut in India with experienced local cooks – compared to the three-stone fire. The lower fuel savings seen in the laboratory may help discourage stove promotion programs from over-stating the fuel savings that will be experienced by rural households, which could lead to dissatisfaction among cooks. The 41% fuel savings that Aprovecho found in the field tests in India closely matches the 38% result from the MVP Ruhiira study, despite different cooking practices. The Aprovecho study also measured stove emissions, finding a 46% reduction in CO and 56% reduction in PM

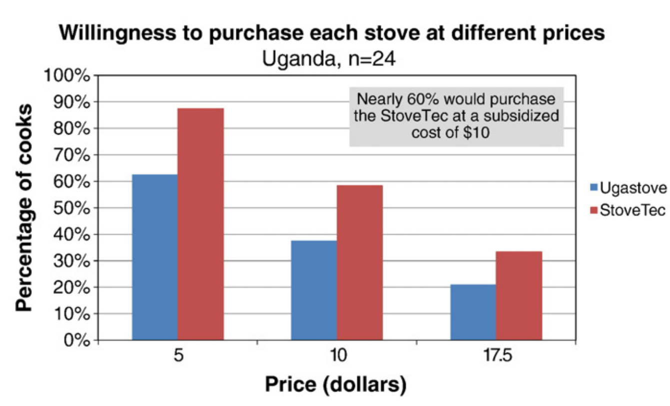

Fig. 12. Percentage of cooks that would purchase stove at each price (Uganda).

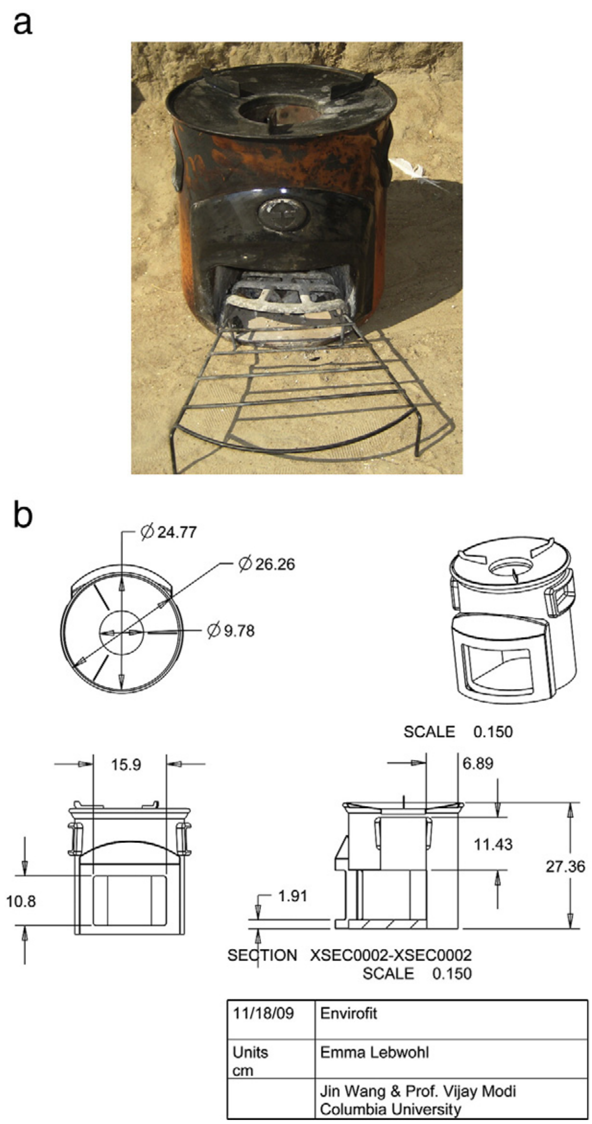

Fig. 13. (a and b): Photo (top) and drawing (bottom) of the Envirofit stove (manufactured in India).

(MacCarty et al., 2008b). Another study by Aprovecho found that the StoveTec stove reduced the global warming impact by 40–60% compared to the three-stone fire (MacCarty et al., 2008a). A comprehensive review of 50 different cookstove models by MacCarty et al. (2010) tested several different Rocket-type stoves, including the StoveTec model with and without various accessories, and found that, on average, the fuel use was reduced 33%, CO emissions by 75%, and PM emissions by 46% in comparison to the three-stone fire.

These findings on fuelwood savings can be combined with data on frequency of cooking various foods in village households to create a rough estimate of yearly fuelwood savings.

In the Uganda study area, households cooked plantains more than any other food, on average, 11 times per week. Across all 60 household tests, the average quantity of food cooked was 3.19 kg, and the average amounts of fuelwood used were 1.77 kg for the three-stone fire, 0.92 for the Ugastove, and 1.04 for the StoveTec. Thus, the average total fuelwood savings for use of the Ugastove in place of the three-stone fire was 0.85 kg/meal, which, multiplied by 11 meals per week and 52 weeks per year, comes to around 490 kg of fuelwood saved per year. Note that this estimate of roughly one half-tonne of fuelwood saved per year is for a household and is limited to cooking of plantains. A similar analysis for the StoveTec stove gives a savings per meal of 0.73 kg, which comes to about 420 kg/year, also a rough estimate, only for cooking plantains. The average size of the households in the Ruhiira village where these cooking tests took place was 6.4, leading to annual per capita fuel savings for cooking plantains of 77 kg for the Ugastove and around 65 kg for the StoveTec.

Mbola village, Tanzania

The second study took place in northwestern Tanzania in an MVP research area surrounding the Mbola village, in the Uyui district located approximately 36 km from the nearest major town of Tabora. A baseline survey of 300 households conducted in 2007 revealed that 97% of all households burn fuelwood in open three-stone fires as the primary means of cooking. Of fuelwood consumed, 98% is collected and less than 1% is purchased.

Cookstoves tested

The three cookstoves of the rocket design tested in this study's “quadruplet” tests were StoveTec, Envirofit and Advent stove, all of which were compared with the traditional three-stone fire. A

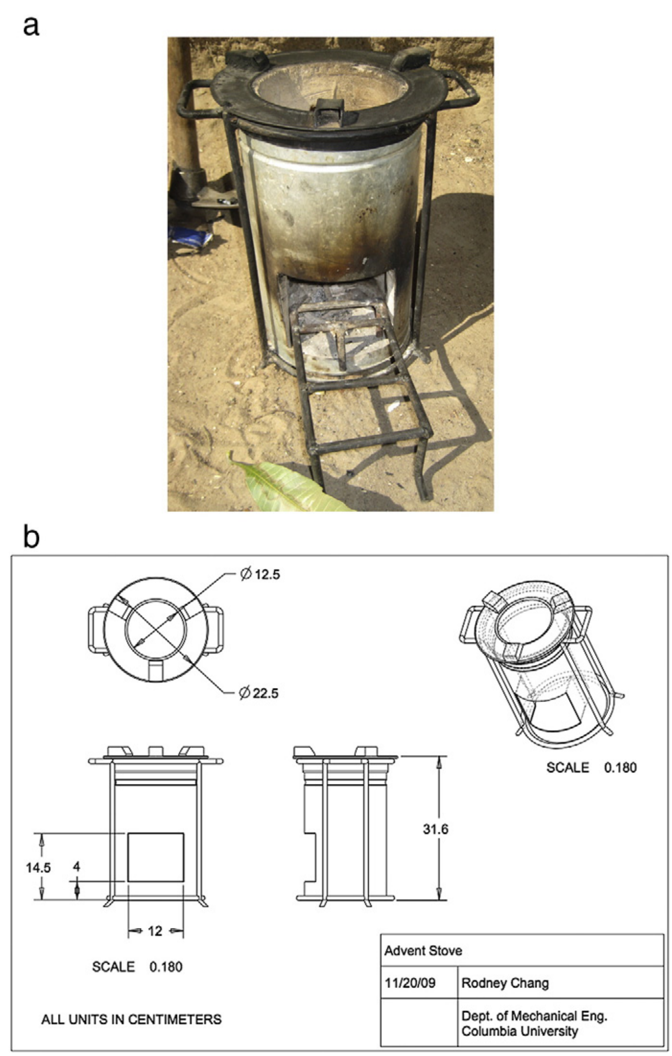

Fig. 14. Photos (top) and drawing (bottom) of the Advent stove (manufactured in Tanzania).

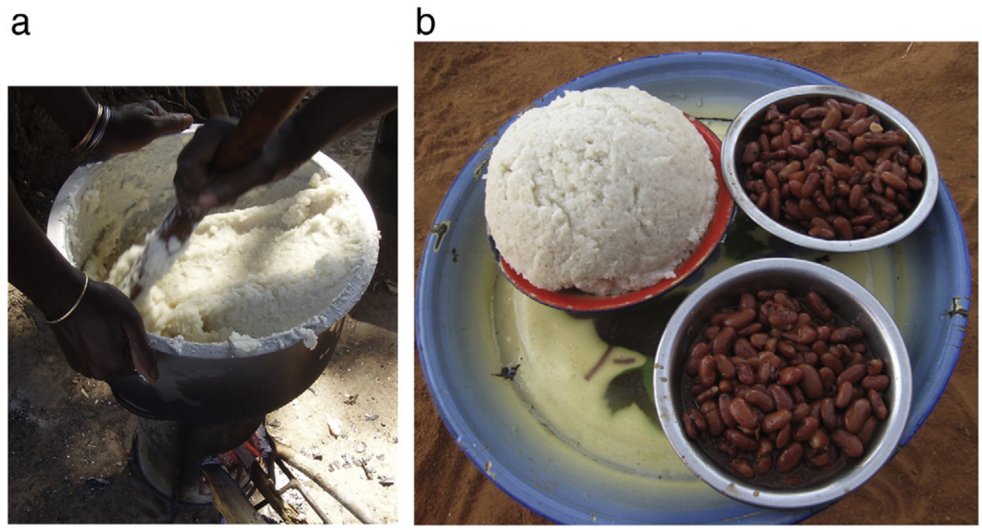

Fig. 15. Stirring of ugali (L); prepared ugali and beans (R).

description of the StoveTec stove appears in Part I. The other two manufactured stoves tested are described below.

Envirofit. The Envirofit stove model G3300 stove (see Fig. 13) was designed by Envirofit International in close cooperation with Oakridge National Research Laboratory in Tennessee, USA, Colorado State University's Engines and Energy Conversion Laboratory, and the Shell Foundation. The stove has a weight of 6.5 kg, with a diameter of 26 cm and height of 27 cm, making it the closest in size to the StoveTec stove. Envirofit stoves are manufactured in India using alloy metal. The bottom of the combustion chamber is made of ceramic.

Advent. The Advent stove (see Fig. 14) is a rocket stove manufactured in Tabora, Tanzania by Advent Technologies. The weight of the stove is around 4 kg, with a diameter of 22 cm and height of 35 cm, making it the smallest manufactured stove tested in either of the two study areas. The combustion chamber is made from a mixture of clay soil and sawdust.

Selected foods and cooking tasks

Ugali (maize flour paste) and beans were the foods chosen for testing. According to information gathered from the preliminary survey, ugali is the food most commonly prepared while beans require the longest cooking time. The average ratio of amount ugali consumed to that of beans for a family per week is about 7:1. See Fig. 15, below, for photos of these foods. Household cooks performed all cooking tasks.

Ugali was tested in 12 households, for a total of 24 tests. For cooking of ugali, the cook lit the fire, boiled water, then added maize flour and stirred until all water was absorbed, forming a paste, and the cook concluded that cooking was complete. The need for frequent stirring of the thick maize paste sometimes required assistance (see Fig. 15, left) and made simultaneous cooking of multiple batches by a single cook impractical, so ugali tests were conducted in random consecutive order. The decision of whether to use the adjustable pot skirt attachment for any stoves was left to each household cook. About half of the cooks used the skirt. For some pots, the skirt was too small.

Beans were tested in 18 households for a total of 36 tests. Beans were not soaked before cooking. The household cook added the specified amount of beans and water to the pot, lit the fire, placed the pot on the cookstove and left the beans to cook, adding water during cooking when needed. Cooks tested the texture and taste of the beans to conclude when cooking was complete.

Test results

Controlled cooking test results. Figs. 16a and b display the average SFC values for each of the manufactured stoves compared to the three-stone fire for beans and ugali tests, respectively. Since tests which used the pot skirt did not show significant fuel savings over the tests that omitted it, all StoveTec results for each food were treated as a single dataset.

Fig. 16c displays the percentage fuel savings for each stove for both foods, relative to the three-stone fire. When beans were tested, the Advent stove had average fuelwood savings of 36% (with a 95% confidence interval ±6%). The StoveTec stove had a statistically similar fuelwood savings of 34% (±6% C.I.). The Envirofit stove demonstrated the lowest average fuelwood savings of 22% (±6% C.I.). When ugali was tested, the StoveTec and Envirofit Stoves showed comparable fuelwood savings of 41% (with 95% confidence intervals of ±12% and ±10% respectively), while the Advent stove showed fuelwood savings of 25% (±14% C.I.).

These results show that while all three manufactured cookstoves save fuelwood for both foods, the StoveTec showed the best performance overall, since its fuel savings were either equal to or better than the Envirofit and Advent stoves for both foods. More specifically, for cooking beans, the fuel savings using the StoveTec stove was higher than the Envirofit, and statistically equal to the Advent; similarly, for cooking ugali, the StoveTec saved more fuel than the Advent, and gave results statistically equal to those for the Envirofit stove. For the ugali tests, the high variance in measurements (resulting in confidence intervals of ±10 to 14%) limits the precision of stove comparisons. However, the much narrower confidence intervals for the beans tests (±6%) indicate that the difference between the two top performing stoves (Advent and StoveTec) and the Envirofit is statistically significant.

Fig. 17 shows changing SFC values with increasing dry weight of beans cooked, which ranged from 0.25 to 1.5 kg, and averaged 0.6 kg for the Tanzania study. As with the plantain cooking data from Uganda, the three-stone fire consistently shows the highest specific fuelwood consumption, and the graph demonstrates a clear downward trend in SFC for all stoves with increasing quantity of beans cooked. Results for ugali (not shown) do indicate higher SFC for the three-stone fire across all data (dry weights from 0.75 to 4 kg, and averaging 1.8 kg) but demonstrate no clear downward trend with increasing weight of food cooked, most likely due to the high variance in the ugali measurements, as noted previously.

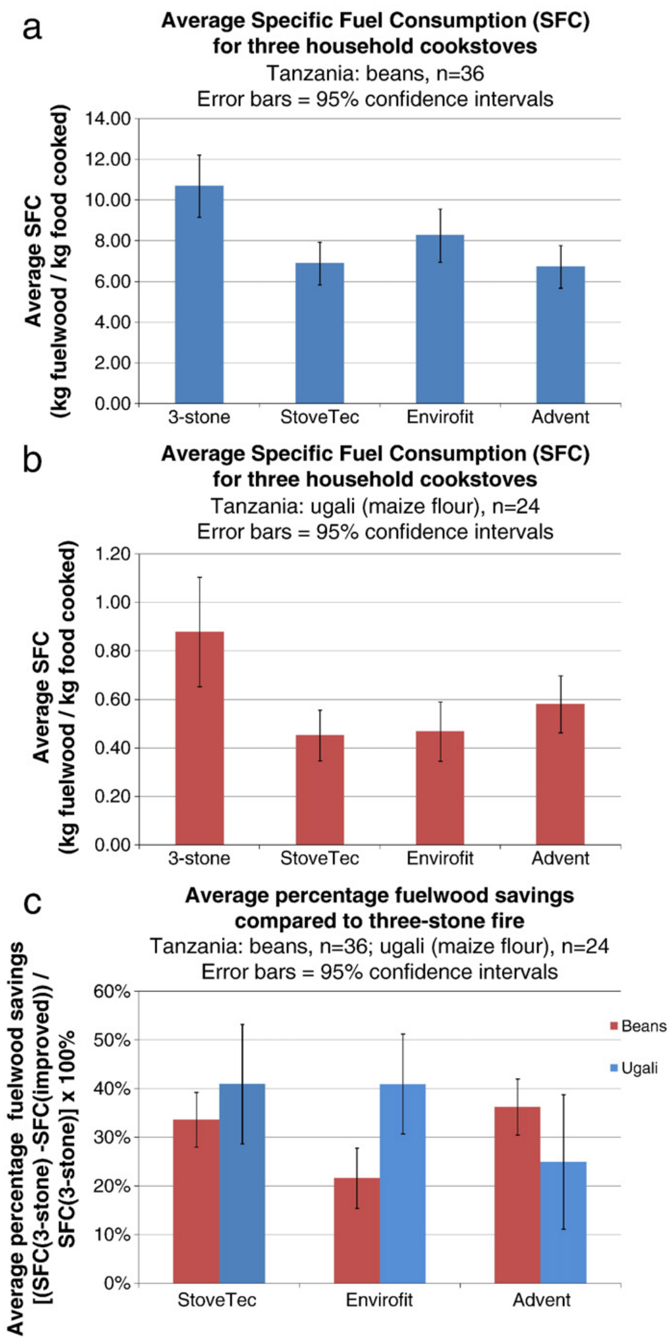

Fig. 16. (a, b, and c): Tanzania "quadruplet" CCT results: SFC values for two foods cooked using three manufactured stoves compared to three-stone fire. (c): Tanzania "quadruplet" CCT results: percentage fuel savings for two foods cooked using three manufactured stoves compared to three-stone fire.

Fig. 18 shows the percentage increase in cooking time from use of the manufactured cookstoves compared to the three-stone fire. In ugali tests using the three-stone fire, the average time was approximately 29 min. The small increases in cooking duration for the StoveTec and the Envirofit (4% and 16%, respectively) were not statistically significant with respect to the three-stone fire or with respect to each other. However, the Advent stove's much greater increase to 47 min (an additional 63%, ±25%) is statistically significant. When beans were tested, the average cooking time for the three-stone fire was 200 min. The StoveTec showed a small and statistically insignificant increase in cooking time (to 206 min), while the Envirofit showed a significant but modest increase to 215 min (an additional 9%, ±5%), and the Advent was only slightly larger at 224 min (an extra 13%, ±5%).

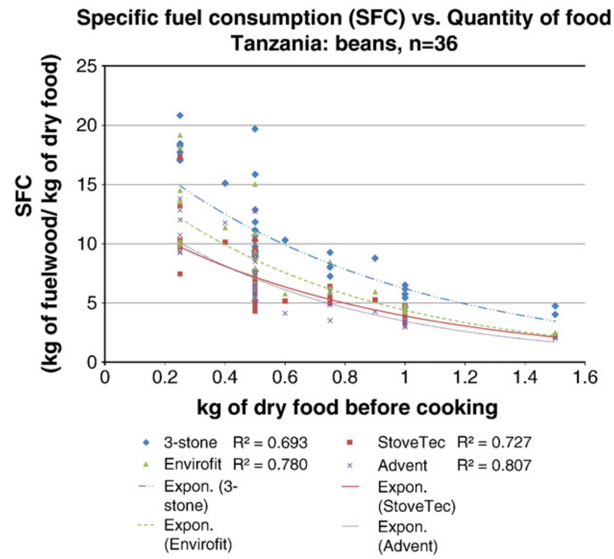

Fig. 17. Fuel consumption trends with mass of food cooked (beans, Tanzania).

Fig. 19 below displays the SFC versus cooking time for all tests for both foods using all cookstoves. The two clusters of data correspond to ugali (lower left) and beans (upper right), and the trendlines show the consistently higher SFC for the three-stone relative to the manufactured stove values clustered below. The data show the widely differing results – a factor of 5 to 10 in overall SFC values – obtainable from conducting tests which include more than one food. Also, the high variance in the data illustrates the need for statistical analysis to clarify significant differences among the three.

Survey results

The Tanzanian cooks' rankings of the stoves are shown in Fig. 20. The StoveTec was rated highest overall by a wide margin, with nearly two-thirds (63%) of respondents ranking it most preferred and 33% rating it second. The Envirofit was rated second overall, with 30% ranking it first and 47% second. The three-stone fire was rated third overall, with 43% ranking it third and 30% ranking it fourth. The Advent was rated last overall, with the majority of respondents (57%) ranking it last, notably lower than the three-stone.

The cooks' reports of what they liked about each manufactured cookstove are shown in Fig. 21. The reasons cited most often for all three stoves together were fuelwood savings (over 80%), lower smoke emissions (over 40%) and that they are easy to light/not affected by

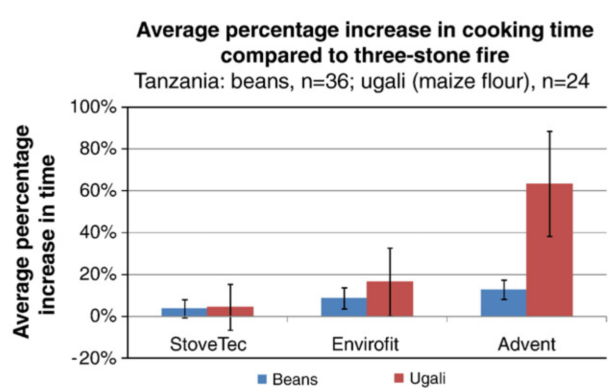

Fig. 18. Percentage increase in cooking time compared to 3-stone fire (beans, ugali; Tanzania).

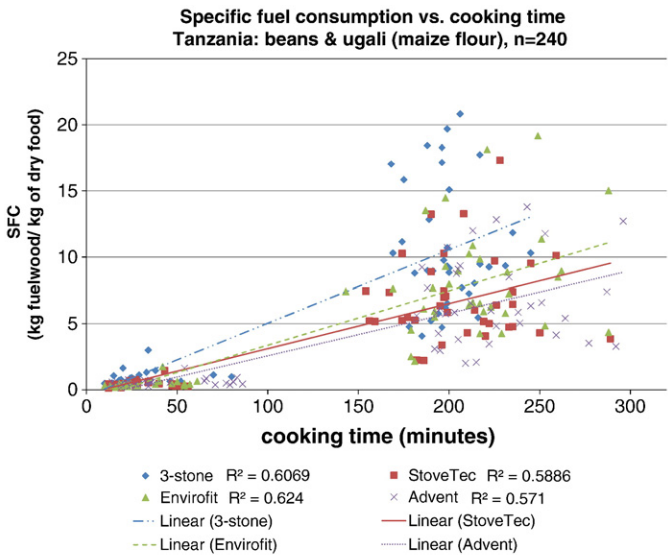

Fig. 19. Specific fuel consumption vs. cooking time (beans, ugali; Tanzania).

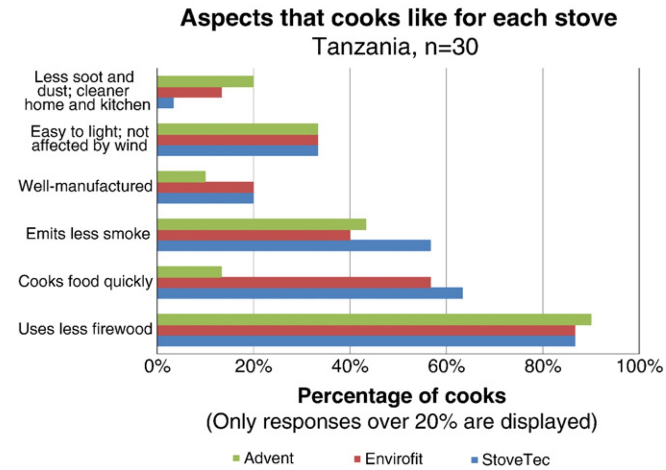

Fig. 21. Results of what users like about the stoves compared to the three-stone fire (Tanzania).

the wind (over 30%). Around 60% of users also liked that the StoveTec and the Envirofit stoves cooked food quickly, though this was only rarely reported for the Advent (13%). Traits respondents disliked are shown in Fig. 22. For the StoveTec and Envirofit stoves, about one-third cited the difficulty in stirring pots and 20% found them to be too small for most cooking tasks; however, nearly half (45%) reported no complaints. In contrast, for the Advent stove, between 50 and 60% complained that it was improperly sized, too tall, and took longer to cook, and less than 10% had no complaints. Nearly half of the cooks stated that the StoveTec and Envirofit models required more tending, but that this was not a problem because they cooked more quickly. For the Advent stove, 40% said that it not only required more tending but also that this was a problem because of the longer cooking time. When asked directly about the size of each manufactured stove, nearly 90% of cooks in the Tanzanian study said that both the StoveTec and Envirofit stoves were the proper size for most cooking tasks. For the Advent stove, however, only one-third said it was properly sized, while two-thirds (63%) reported that it was too small. Note that both figures only display responses that reached a “threshold” of 20% of respondents for at least one stove.

Fig. 23 displays a histogram of the sizes of the most frequently used pots in Tanzanian study area, with vertical lines indicating the diameters for different features (tops and pot skirts) of the cookstoves tested. Overall, there is fairly close agreement between common pot sizes and diameters of the stove tops. However, the differences in size and shape (the Advent has a much narrower profile than other improved stoves) appear to have been decisive, since many cooks concluded that the height and diameter of the Advent stove make it inappropriate for a number of cooking tasks.

Fig. 24 shows the percentage of household cooks that said they would buy each manufactured cookstove at three specified prices. Both the StoveTec and Advent stoves are predicted to have a full retail cost in the Tanzania village test area of approximately $17–24, with a conservative estimate of $20–22. The Envirofit's expected retail cost is $35 however no cooks reported would buy it at that price. Willingness to pay is low (below 20% for all stoves) at $17.50. If the stove price was subsidized to reduce the retail price to $10, the willingness to purchase rises to over 60% for the StoveTec and Envirofit, but only 13% for the Advent stove.

In summary, the StoveTec and Envirofit stoves showed similar results for the questions of stove ranking, size and usability from the survey, while the Advent stove scored substantially lower on each of these. Key complaints about the Advent stove included its overall size and shape, as well as longer cooking times, particularly for ugali, the most commonly cooked food in the study area.

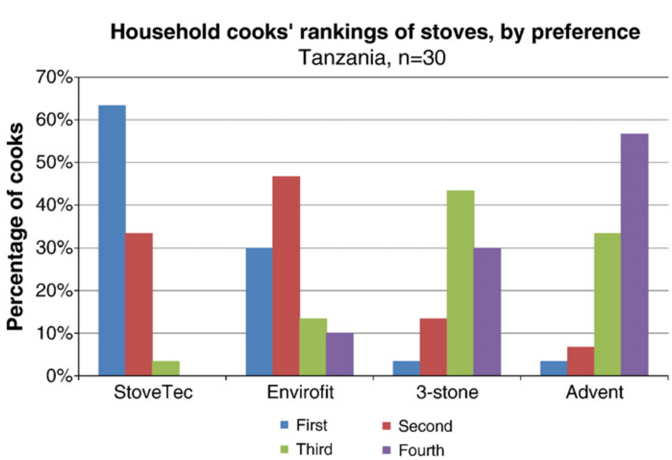

Fig. 20. Rank of preferences for stoves (Tanzania).

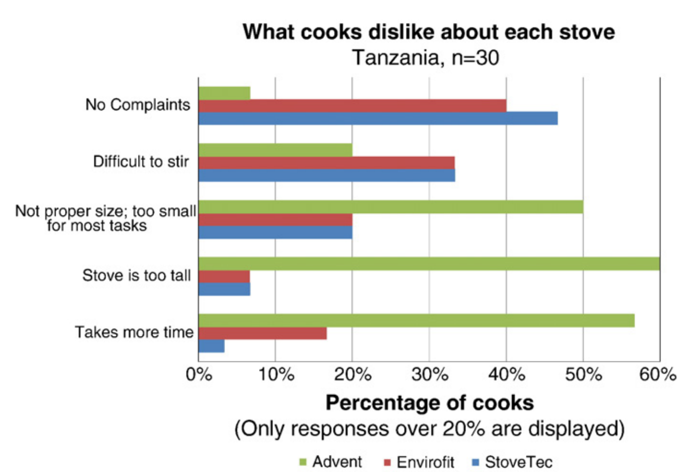

Fig. 22. Results of what users dislike about the stoves compared to the three-stone fire (Tanzania).

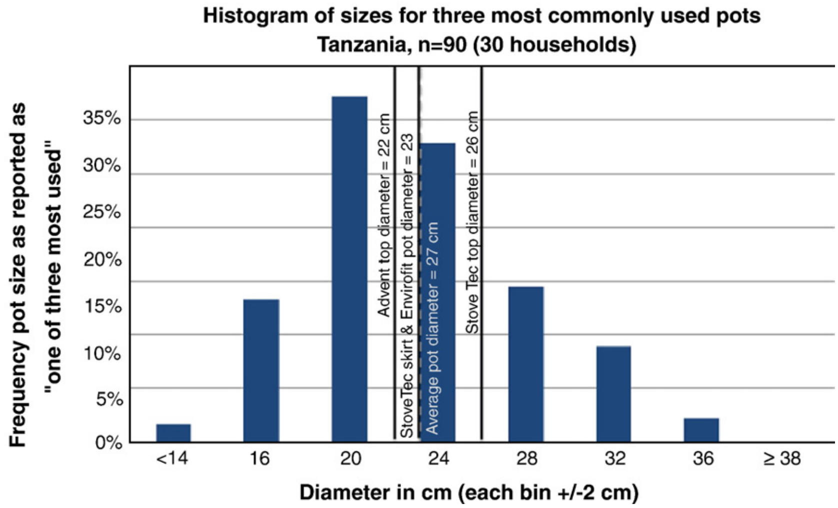

Fig. 23. Size comparison of stoves and commonly used pots (Tanzania).

Discussion of results from Mbola, Tanzania

Citing a combination of fuel savings, cooking time, and multiple factors contributing to overall usability, the cooks in the Mbola, Tanzania study consistently rated both imported manufactured stoves above the locally-made Advent model. For the two imported stoves, although the size, shape and overall usability seem comparable, the StoveTec was clearly preferred over the Envirofit. The primary reasons appear to be the greater fuel savings that the StoveTec delivered in one of the two cooking tests, and the StoveTec's shorter cooking time for both tests. Despite its comparable overall fuel savings, the Advent stove was strongly disliked by cooks, who preferred even the three-stone fire, primarily because of the Advent stove's overall design and extended cooking time. Survey results demonstrate that both the StoveTec and Envirofit stoves would be used on a regular basis for most cooking tasks, though the Advent stove would not be used as often and only then for specific tasks.

These results also demonstrate the importance of testing a range of foods representative of local household cooking practices and dominant modes of fuel use. The choice of test foods may not be initially obvious. In the case of the Tanzania study area, the greater frequency of cooking ugali (about seven times as often as beans) suggest this food as the clear choice for a stove evaluation with fuel savings as the primary criterion. However, the much greater fuel consumption per meal of beans (with 5-10 times larger SFC values than ugali) suggests that these two foods are of comparable importance to ensure measurements relevant to the overwhelming majority of fuel use in the area. The tests conducted here omitted only food items such as meat, greens or tea which were cooked less frequently and in small quantities or required relatively little fuelwood. Convenience and usability are also key factors in stove assessment, and the cooking needs for the two foods chosen for testing differ in ways that affect these dramatically. Ugali requires a relatively short cooking time and frequent, vigorous stirring with assistance from another cook, whereas beans require more time but little physical action to cook. Fuel consumption aside, it appears that the usability advantages in cooking ugali were decisive in cooks' preference ratings. Longer cooking time for ugali was seen by cooks as a major drawback for both the Advent and Envirofit stoves. Similarly, although the Advent stove had the greatest fuelwood savings for cooking beans, it was rated last overall, most likely due to much longer cooking time for ugali plus inconvenience of the Advent's size and shape for the stirring that this maize meal paste requires. These important comparisons would not be possible if the testing program had been limited to a single food or variable, or to a laboratory setting.

Fig. 24. Percentage of users that would buy stoves at specified price (Tanzania).

No peer-reviewed studies were found for the Envirofit or Advent stoves to use for comparison, however more informal sources were available. The promotional literature from the Envirofit stove manufacturer claims "up to 60% less biomass fuel (wood, crop waste, etc)" consumption, and shows the Envirofit stove's energy consumption to be more than 40% lower than that of an unspecified "rocket stove" on a chart of results from water boiling tests (unpublished research, Colorado State University, Engines and Energy Conversion Laboratory, obtained from www.shellfoundation.org website accessed Jan 11, 2009). Results from the modified CCTs conducted for this Tanzania study show fuel savings from the Envirofit in the range of roughly 20–40% over the three-stone fire with equal or slightly longer cooking times. In the Tanzania CCT study, when compared with the StoveTec rocket stove design, the Envirofit's performance is comparable for ugali and slightly less favorable for beans. However, as stated previously regarding the Uganda study, past experience has shown that WBTs and modified CCTs can be difficult to compare, and results from the WBT are not necessarily indicative of results in field kitchens. Moreover, foods, cooking practices and prevailing conditions in other studies may differ markedly from those of this Tanzania study. No comparable public claim for fuel savings for the Advent could be obtained, but informally, Advent promoters report fuel savings of approximately 40%, based on CCTs conducted in Dar Es Salaam, Tanzania (ProBEC Tabora, Tanzania, 2010). This is consistent with results obtained in this experiment for beans, though it falls at the outer edge of our 95% confidence interval for ugali.

As in the Uganda case, data on fuelwood savings and cooking frequency for foods cooked in the Tanzania study can be used to create a rough estimate of yearly fuelwood savings for these two dishes. Since the two foods chosen are the most frequently cooked (ugali) and the most fuel-intensive (beans), they can be considered the best candidates for this estimate. In the Tanzania study area, households cooked ugali more often than any other food, 10 times per week, on average. Average fuelwood consumption per meal was 1.63 kg with a three-stone fire, compared with 0.79 kg with the StoveTec stove, 0.89 kg with the Envirofit stove, and 1.04 kg with the Advent stove. For beans, which are cooked on average 2.5 times per week, cooking with the three-stone fire consumes 5.5 kg per meal, compared with 3.5 kg for the StoveTec and 4.2 kg for the Advent. When all fuelwood consumption values for each stove are multiplied by the frequency each food is cooked per week, and by 52 weeks per year, the yearly fuelwood savings, for both foods combined, are about 700 kg for the StoveTec, around 560 kg for the Envirofit, and about 590 kg for the Advent. The average size of the households where these tests took place was 7.6, leading to annual per capita fuel savings values of 92 kg for the StoveTec, around 74 kg for the Envirofit, and about 78 kg for the Advent. Note that this assumes that all cooking of both of these foods is done using the improved stoves, though this may not be possible if both beans and ugali are cooked in the same meal.

Conclusions (both tests)

The fuel saving benefits of the improved stoves were generally clear and quantifiable, and, the imported stoves were seen as preferable to the three-stone fire. These results are summarized in Table A1 in Appendix A. All manufactured cookstoves tested in these field settings showed substantial and statistically significant fuelwood savings relative to the three-stone fire, with average values from 22% to 46%, depending upon the stove and food combination. Use of any manufactured cookstoves also led to an increase in cooking time, though these increases tended to be small or statistically insignificant for the imported stoves (StoveTec, Envirofit) and larger for the locally-made stoves (Ugastove, Advent). Usability questionnaires illustrated which factors – such as cooking time, stove size, and need for tending – were decisive for household cooks. The StoveTec performed the best overall, with substantial fuelwood savings for all cooking tests and high user rankings in both studies. Though the other three stoves were not compared directly against one another, results suggest that the Envirofit stove ranked second, overall, while the two locally-made stoves were ranked lower, in one case below the three-stone fire.

The results highlighted the importance of trials including simultaneous tests of multiple cookstoves in household kitchens, investigating both stove performance and user preference while cooking at least two foods with differing cooking time and fuel intensity. The relative performance of some stoves for key parameters (cooking time and specific fuelwood consumption) varied substantially with the food cooked. Moreover, tests of different foods allowed cooks to experience different usability challenges, such as the need for stirring or tending. It is safe to assume that this range of quantitative and qualitative factors could not be as effectively investigated in a laboratory setting or in field tests limited to a single food or manufactured stove. Also, because fuel savings, decreased cooking time, and improved overall usability are all potentially competing design goals, the safest approach to evaluating stoves is likely to be to allow cooks in a given community to assess and prioritize these multiple aspects of user satisfaction themselves. Thus, while additional laboratory and design research are certainly important, they should not be seen as a substitute for field tests.

This study could not assess performance and user preference over long-term use. The stove with the longest stated lifetime (according to the manufacturer's guarantee) is the Envirofit, with 5 years. The StoveTec is expected to last 2 years, possibly more. The Ugastove and Advent stoves are expected to last between one and two years. Cooks participating in this study had used the stoves for between one week and one month and so were somewhat experienced with the stoves and familiar with the benefits. However, it is unclear if they would adjust cooking practices over time, or if more or less familiarity with the stoves' expected lifetime would affect factors such as relative willingness to pay. The price at which 50% or more cooks said they would adopt the two most preferred stoves (StoveTec and Envirofit) was $10.

Fig. 25 shows how many separate fires households typically cook with simultaneously for each meal in the Uganda and Tanzania study areas. For breakfast, in both sites, most households currently only use one fire, though in Uganda the tendency to serve no meal at breakfast time is more common. For lunch, again in both sites, households are roughly evenly divided among those who use one or two fires simultaneously. Dinner shows some divergence between the two study areas, with Ugandan cooks tending to use two fires, while Tanzanian cooks tend toward one. In both sites, three fires are only rarely used for lunch and dinner.

Cooks were also asked the number of hours spent cooking in the previous day and how many of those hours include cooking on two or more fires simultaneously. For the Ugandan cooks, the average total cooking time per day was 3.8 h, of which 1.7 h (or 44%) was spent cooking with two or more fires. For the Tanzanian cooks, the responses were 3 h total with 2.5 h using two or more fires (82%). Finally, cooks were asked whether they would still use the three-stone fire at all if they owned one or two improved stoves. In Uganda,

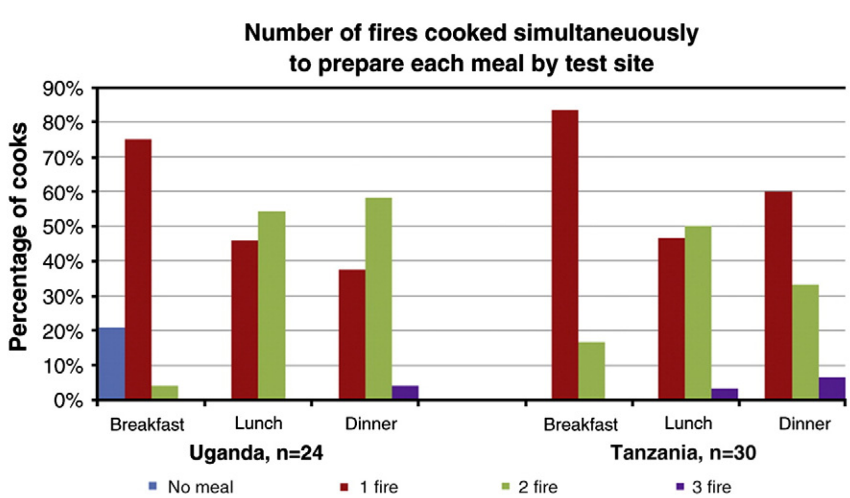

Fig. 25. Number of fires cooked simultaneously to prepare each meal.

75% of respondents stated that they would still use the three-stone fire for some tasks if they owned one improved stove, though this fell to 8% if these cooks owned two improved stoves. Two-thirds of Tanzanian cooks said they would continue to use a three-stone if they owned only one improved stove, versus one-third if they owned two.

Based on these data from multiple questions, a very rough and conservative estimate can be made that between 50 and 60% of household cooking would likely be performed on a manufactured stove if a household only owned one, with the remainder of cooking probably being done using a second fire of the three-stone type. This is assuming that basic patterns of multiple stove use would remain unchanged and that the improved stove is used preferentially, in place of the three-stone fire for all single-fire cooking, and half of the cooking with two or more stoves. This has important implications for design of interventions using improved cookstoves. The use of multiple stoves is likely to similarly complicate efforts to improve indoor air quality through the use of improved stoves, though this is beyond the scope of this study.

A generally accepted value for household biomass use for cooking in sub-Saharan Africa ranges from 2.5 to 3 tonnes per year. The estimates above suggesting that only 50–60% of cooking would be performed with an improved stove if only one were owned, along with testing data from Uganda and Tanzania suggesting that a biomass cookstove might be expected to save 30–40%, the expected fuelwood savings per year can be predicted (using the mid-points of each range) to be roughly:

$$55\% \times 35\% \times 2.75\,\text{tonnes} = {\sim}530\,\text{kg}$$

This agrees fairly well with the estimates from both study areas provided earlier, but computed in a different manner, that a household will save somewhere in the range of 420 to 490 kg per year, for only one food in Uganda, or from 560 to 700 kg per year in Tanzania, cooking two foods. Thus, overall, one half-tonne per year appears to be a credible estimate of yearly fuelwood savings from ownership of one improved StoveTec or Envirofit cookstove.

These results, particularly confirming fuel savings and villagers' willingness to pay for improved stoves, have suggested potential for scaling up improved household stove programs within the Millennium Villages Project. The general approach has been to introduce stoves through a period of testing, which builds local demand while providing users with an opportunity to compare imported and locally-made improved stoves with the three-stone fire, enabling informed local decision-making regarding stove purchase. Afterward, based on stove preferences identified through the testing and user survey, the MVP assists with local or international procurement of stoves and establishment of mechanisms for local sale, encouraging market-based, demand-driven dissemination. Following this model, additional stove testing and introduction efforts have been initiated or are planned for MVP sites in Nigeria, Malawi, Mali and Senegal. Given the complexities of establishing stove manufacturing procedures, particularly quality control related to clay mixing and firing, the MVP has not undertaken stove manufacturing programs, however the project does procure stoves locally if a domestic supplier is able to produce in volume (approximately 1000 stoves, or more). However, a full discussion of the MVP stove commercialization programs is beyond the scope of this paper.

Still, some pending issues should be identified as key areas for future study, including: the impact of stoves on indoor air quality; the potential for improvement of international supply chains of stoves produced in Asia for sale in sub-Saharan Africa; and the potential for increased local production in sub-Saharan Africa of stoves with confirmed fuel savings and air quality improvements.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.esd.2010.07.003.

References

Bailis R. Stove Performance Testing Protocols, Controlled Cooking Test (CCT) Version 2.0. Shell Foundation. University of California Berkeley; 2004.

Berrueta V, Edwards R, Masera O. Energy performance of wood-burning cookstoves in Michoacan, Mexico. Renewable Energy 2008;33(5):859–70.

Colorado State University Engines and Energy Conversion Laboratory. http://www.shellfoundation.org/admin/upload_img/images/Efit%203rd%20Gen%20Stoves.pdf, accessed January 11, 2009.

Haigler E, Arineitwe Ndemere J, Pennise D. Investigation of Fuel Use for Urban Community Development Association's Wood and Charcoal Domestic Stoves. Center for Entrepreneurship in International Health and Development (CEIHD). University of California-Berkeley; 2007.

Jetter J, Kariher P. Solid-fuel household cook stoves: characterization of performance and emissions. Biomass and Bioenergy 2009;33:294–305.

MacCarty N, Ogle D, Still D, Bond T, Roden C. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy for Sustainable Development 2008a;12(2):56–65.

MacCarty N, Still D, Ogle D, Drouin T. Assessing Cook Stove Performance: Field and Lab Studies of Three Rocket Stoves Comparing the Open Fire and Traditional Stoves in Tamil Nadu, India on Measures of Time to Cook, Fuel Use, Total Emissions, and Indoor Air Pollution. Aprovecho Research Center; 2008b.

MacCarty N, Still D, Ogle D. Fuel Use and Emissions Performance of Fifty Cooking Stoves in the Laboratory and Related Benchmarks of Performance. Energy for Sustainable Development 2010;14:161–71.

Majogoro M, ProBEC Tabora. Personal Correspondence; 2010. January 19.

National Forest Authority of Uganda. Ruhiira Wood Supply Report; 2007.

Quadir SA, Mathur SS, Kandpal TC. Barriers to Dissemination of Renewable Energy Technologies for Cooking. Energy Conversion and Management 1995;36(12):1129–32.

Rehfuess E. Fuel for Life: Household Energy and Health. Geneva, Switzerland: World Health Organization; 2006.

Rehfuess E, Mehta S, Prüss-Üstun A. Assessing household solid fuel use: multiple implications for the millennium development goals. Environmental Health Perspectives 2006;3:373–87.

Sanchez PA, Palm CA, Sachs JD, Denning GL, Flor R, Harawa J, et al. The African millennium villages. Proceedings of the National Academy of Sciences. Proceedings of the National Academy of Sciences 2007;104(43):16775–80.

Smith K, Dutta K, Chengappa C, Gusain PPS, Masera O, Berrueta V, et al. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the Household Energy and Health Project. Energy for Sustainable Development. 2007;12(2):5-18.

Wallmo K, Jacobson S. A social and environmental evaluation of fuel-efficient cook-stoves and conservation in Uganda. Environmental Conservation 1997:99-108.

Winiarski L. Design Principles for Wood Burning Cook Stoves. Aprovecho Research Center, Partnership for Clean Indoor Air, Shell Foundation; 2005.