Environmental Research Letters

LETTER • OPEN ACCESS

A quantitative performance assessment of improved cooking stoves and traditional three-stone-fire stoves using a two-pot test design in Chamwino, Dodoma, Tanzania

To cite this article: J Hafner *et al* 2018 *Environ. Res. Lett.* **13** 025002

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
13 February 2017

REVISED
6 November 2017

ACCEPTED FOR PUBLICATION
28 November 2017

PUBLISHED
29 January 2018

LETTER

A quantitative performance assessment of improved cooking stoves and traditional three-stone-fire stoves using a two-pot test design in Chamwino, Dodoma, Tanzania

J Hafner[1,5], G Uckert[1], F Graef[2], H Hoffmann[1], A A Kimaro[3], O Sererya[4] and S Sieber[1]

1 Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Socio-Economics, Eberswalder Street 84, 15374 Müncheberg, Germany
2 Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Land Use Systems, Eberswalder Street 84, 15374 Müncheberg, Germany
3 World Agroforestry Centre (ICRAF), MARI Mikocheni, PO Box 6226, Dar es Salaam, Tanzania
4 Ministry of Natural Resources and Tourism, PO Box 191, Kidatu–Morogoro, Tanzania
5 Author to whom any correspondence should be addressed.

E-mail: johanneshafner@gmx.net

Keywords: improved cooking stoves, Tanzania, firewood, energy efficiency, three-stone-fire-stoves, traditional cooking energy, semi-arid region

Abstract

In Tanzania, a majority of rural residents cook using firewood-based three-stone-fire stoves. In this study, quantitative performance differences between technologically advanced improved cooking stoves and three-stone-fire stoves are analysed.

We test the performance of improved cooking stoves and three-stone-fire stoves using local cooks, foods, and fuels, in the semi-arid region of Dodoma in Tanzania. We used the cooking protocol of the Controlled Cooking Test following a two-pot test design. The findings of the study suggest that improved cooking stoves use less firewood and less time than three-stone-fire stoves to conduct a predefined cooking task.

In total, 40 households were assessed and ask to complete two different cooking tasks: (1) a fast cooking meal (rice and vegetables) and (2) a slow cooking meal (beans and rice). For cooking task 1, the results show a significant reduction in firewood consumption of 37.1% by improved cooking stoves compared to traditional three-stone-fire stoves; for cooking task 2 a reduction of 15.6% is found. In addition, it was found that the time needed to conduct cooking tasks 1 and 2 was significantly reduced by 26.8% and 22.8% respectively, when improved cooking stoves were used instead of three-stone-fire-stoves.

We observed that the villagers altered the initial improved cooking stove design, resulting in the so-called modified improved cooking stove. In an additional Controlled Cooking Test, we conducted cooking task 3: a very fast cooking meal (maize flour and vegetables) within 32 households. Significant changes between the initial and modified improved cooking stoves regarding firewood and time consumption were not detected.

However, analyses show that both firewood and time consumption during cooking was reduced when large amounts (for 6–7 household members) of food were prepared instead of small amounts (for 2–3 household members).

Introduction

The importance of forests and woodlands for human life is manifold. Forests are crucial for livelihoods, providing direct benefits like firewood, charcoal, timber, animal and human food, and medical services, among others (Chhatre and Agrawal 2008, Campbell *et al* 1996). Forests are also important for regulating the climate, mitigating the negative effects of climate change, conserving soil and water sources, as well as providing living space for numerous animals and plants (Moffat 1997).

On a global scale, around 2.7 billion people, of which approximately 90% live in developing countries (Urmee and Gyamfi 2014), still depend on traditional biomass energy, such as firewood, charcoal, crop residues, and dung, for both cooking and heating (Raman *et al* 2013) and will do so in the future (Kees and Feldmann 2011, Iiyama *et al* 2014); similar numbers are also reported by Shrimali *et al* 2011 (2.5 billion), Bailis *et al* 2015 (2.8 billion), and Jagger and Shively 2014 (3.0 billion). The IEA (2016) reports that in 2040, 1.8 billion people will remain reliant on traditional biomass energy as a cooking fuel, with the overwhelming majority living in Sub-Saharan Africa (SSA).

In Tanzania, the controversial topic of deforestation has been discussed since the 1950s (Troil Von 1992). Overexploitation of forest resources leads to forest degradation with multiple negative effects for human livelihoods. However, at the same time forest resources are the economic and social basis for hundreds of thousands of citizens (Openshaw 2010). In 2005, the total forest cover in the whole country was 35 257 000 ha, with annual forest loss estimated to be approximately 400 000 ha (FAO 2010, Blomley and Iddi 2009); although other studies have different conclusions: Msuya *et al* (2011) state 150 433 ha and Ylhäisi (2003) 100 000 ha per year. Even if forest degradation continues only at a rate of 1% annually, the remaining forested areas will be depleted by 2100 (Msuya *et al* 2011).

The share of wood used as firewood out of the total amount of wood harvested is substantial. More than 50% of wood harvested in developing countries is used as firewood or for charcoal production. Important drivers of cooking related firewood consumption are income and population growth (Scherr 2004).

The demand for wood as a cooking fuel is one of several factors contributing to deforestation in Tanzania (Angelsen and Kaimowitz 1999). Scholars cite that 95% of households use firewood as a source of energy for cooking, with 4% relying on charcoal and 1% on crop residues (Sander *et al* 2013). Kassenga (1997) emphasizes that biomass is the most important energy source in Tanzania, accounting for about 90% of total energy consumption, helping to meet the demand for energy for cooking and heating (Desai *et al* 2004, Wiskerke *et al* 2010). The overexploitation of wood resources results in reduced wood availability and longer distances for villagers to walk to collect firewood. For example, in 2000, people in the arid region of Singida travelled more than 10 km to collect wood (IEA 2006), a 10 h return trip (Johnson 1999).

Because of its multiple socio-economic benefits, improved cooking stove (ICS)[6] technologies have the potential to replace the traditional three-stone-fire (TSF) stoves in rural Tanzania, thus potentially reducing cooking-related firewood consumption (Zein-Elabdin 1997, Ochieng *et al* 2013). With its higher thermal efficiency, the introduction of ICSs can reduce the absolute amount of biomass needed for cooking compared to TSF stoves. The thermal efficiency of TSF stoves is cited to be between 7% and 12% and therefore below ICSs (Wiskerke *et al* 2010). In addition to reducing firewood consumption, ICSs can help rural households minimize the adverse health effects of indoor air pollution (Jetter and Kariher 2009, WHO 2015). This is in line with Bond *et al* (2013), who report reduced indoor air pollution resulting from using ICSs. Traditional means of cooking are closely linked to negative consequences for health, the environment, and socio-economic development (Stanistreet *et al* 2014, Blin *et al* 2013). Every year, smoke and particle inhalation from TSF stoves causes millions of respiratory infections and more than 4 million deaths, of which more than 50% are children younger than 5 (Lim *et al* 2013, Dherani *et al* 2008, WHO 2015). However, substantial health benefits resulting from the introduction of ICSs can only be realized once the baseline technology (TSF stoves) is replaced (Johnson and Chiang 2015).

Research gap and aim

Although firewood scarcity has reached an alarming extent in the semi-arid region of Dodoma in Tanzania, field-based analyses of TSF stoves and ICSs regarding firewood and time consumption are not available for the region. In order to contribute to adoption and knowledge based uptake of ICSs with a two-pot design, this study seeks to provide evidence based results on the performance of ICSs and TSF stoves via a Controlled Cooking Test (CCT). The study was conducted in Idifu village, where a recent ICS intervention resulted in a large number of newly adopted ICSs. Six months since the ICS implementation, we found that local farmers modified the initial ICS design. Therefore, besides comparing TSF stoves and initial ICSs, we additionally investigated whether the locally induced design modifications of initial ICS might have changed performance indicators of ICSs.

Materials and methods

Study area

This study was conducted in the village of Idifu, located in the Chamwino district in Dodoma region, Tanzania. Idifu has a population of approximately 6000 inhabitants. The Dodoma region is semi-arid (350–500 mm) with one short rainy season from December to

[6] The term improved cooking stove does not pre-suppose any technical improvements. The term only indicates a different cooking technology. Improvements depend not only on the technology but also on other factors like the operators or the fuel used.

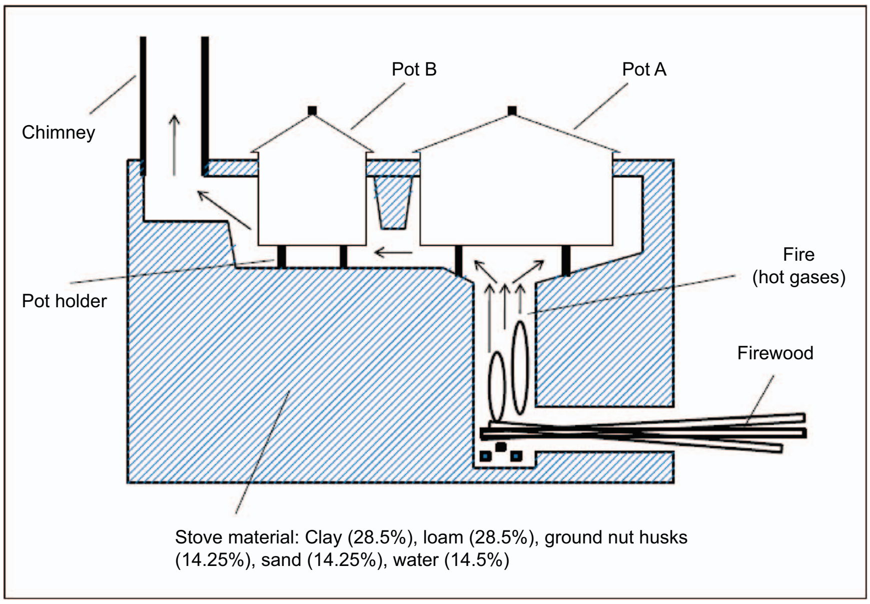

Figure 1. Archetype of an improved cooking stove in Idifu village.

April characterized by sporadic rainfall patterns (Mahoo *et al* 1999). Dodoma's forested area is estimated to cover 4 183 192 ha (NAFORMA 2015).

Construction and design of TSF stoves, initial ICSs and modified ICSs

The ICSs examined in this study use a two-pot design that allows for cooking two dishes at the same time (figure 1). The ICS stove design follows the rocket stove principle, available since the 1980s (MacCarty *et al* 2010), whereby hot air is channeled through the vertical duct. The ICS model used in this study has improved insulation, which seeks to maintain higher thermal efficiency compared TSF stoves by using organic material such as chopped grass and groundnut husks as construction material. The stove has a single combustion chamber that is located below pot A. Pot B is heated via hot air that is channeled through the stove. The incorporated chimney creates a draught that pulls the air from the wood entry slot via pot A and pot B toward the exhaust. Once the fire is lit, the wood entry slot can be closed to slow down the combustion of the firewood when extensive heat is not needed, and simmering is desired (Barnes *et al* 1993). In consultation with local users, the ICS was named *Salama stove* (Kiswahili for safety, security). The name was chosen to highlight the multiple socio-economic benefits connected to the technology. The implementation process of the ICS technology followed a 'Training-of-Trainers' concept. In a collaborative effort, locals were trained to become stove artisans to design, construct, and maintain the ICSs. This knowledge transfer resulted in the establishment of local expertise on stove construction within the community[7]. The input materials for the stove construction were available within the project villages. In order to prevent cracks, it was ensured that the stoves were fully dried (approximately 10 days) before first use.

Since the introduction of the initial ICS in Idifu in February 2015, an artisan-induced design shift emanated from the villagers. Stove producers altered the original stove model with an innovative design change that resulted in the modified ICS. In figure 2, the traditional TSF stove (left), the initial ICS (middle), and the modified ICS are shown.

In August 2015, the ICS design change was first observed, approximately six months after the initial ICS model was introduced. The differences between the initial and the modified type of ICS are found within the stove dimensions (stove height, length, width) and the diameter of the wood entry slot (table 1). In addition, the connection channel between pot A and pot B was altered. Modified ICSs are more frequently constructed with a vertical connection channel instead of a horizontal one.

Controlled cooking test

We used the CCT to assess the quantitative stove performance aspects of TSF stoves, the initial ICS, and the modified ICS with regard to firewood and time consumption. The field-based CCT design evolved from efforts in the 1980s by VITA International Standards (VITA 1985). The CCT is an efficacy test that is designed to assess actual impacts on household fuel consumption using locally available fuels, pots, and local cooks (Kshirsagar and Kalamkar 2014).

[7] The implementation and monitoring of the ICS programme was done within the Trans-SEC project. The implementation of the ICSs was facilitated by the Leibniz-Center for Agricultural Landscape Research (ZALF), MVIWATA (Mtandao wa Vikundi vya Wakulima wa Tanzania) Tanzania and Agricultural Research Centers of Hombolo and Matukupora in Tanzania.

Figure 2. Examples of a TSF stove (left); an initial ICS (middle); and a modified ICS (right).

Table 1. Design features of the initial ICS and the modified ICS.

Construction features	Initial ICS ($N=28$)	Modified ICS ($N=36$)
Stove height[a]	43.3 cm (SD 8.0 cm)	30.5 cm (SD 2.3 cm)
Stove length[a]	115.3 cm (SD 23.0 cm)	98.6 cm (SD 11.3 cm)
Stove width	56.8 cm (SD 4.6 cm)	48.8 cm (SD 5.2 cm)
Diameter of the wood entry slot[a]	12.9 cm (SD 2.6 cm)	14.2 cm (SD 2.4 cm)
Connection channel (horizontal)	75%	44.4%
Connection channel (vertical)	25%	55.6%

[a] Significant differences at a level of significance of 0.05.

We adjusted the CCT test towards the two-pot design of the ICSs in Idifu in order to monitor the important practice of cooking with two pots at the same time.

We conducted two CCTs one year after the introduction of ICSs in the village. The households were selected randomly from across the entire village in order to avoid bias due to differing household economic endowments. Households using TSF stoves, the initial ICS, or the modified ICS as their primary means of cooking were asked to take part in the CCT. We selected cooks who had more than 4 weeks of cooking experience with the stove type in order to reduce bias due to inexperienced cooks.

In total, two CCTs were conducted in Idifu, both in the same season—January and February 2016—with similar weather conditions in order to avoid bias due to different climatic conditions. During the two CCT tests, a total of 72 households were assessed. Each selected household conducted two cooking tasks per day, resulting in 140 test samples. The daily test routine was standardized. In January 2016, 40 households were assessed (20 TSF stoves; 20 initial ICSs). In February 2016 32 households were assessed (13 initial ICSs; 19 modified ICSs). The testing protocols followed Bailis (2004), measuring the firewood consumption and cooking time of TSF stoves, initial ICSs, and modified ICSs during different predetermined cooking tasks.

Testing procedures

Standardized testing procedures and testing utensils (pots, firewood) were used. In all cases, the person generally responsible for cooking in the household was asked to perform the cooking task. The cooks were instructed to use the stoves according to their daily cooking routine. We asked the cooks to cover the pots during the cooking in order to minimize energy loss. The ingredients used were predetermined in type and quantity; 'external' inputs were not allowed.

Firewood consumption was determined at the end of each cooking task. In order to maintain a standardized finish point of cooking, the time was recorded after the water was fully evaporated (cooking task 1), the beans were soft (cooking task 2), and when the porridge had a predefined consistency (cooking task 3). Due to firewood scarcity, two different firewood species were used during the two cooking tasks. The first CCT was performed with a wood species called mrama; the second used mtema. Both species are commonly used as firewood in Idifu. The testing team provided a uniform type (similar size) and moisture status of the firewood to avoid bias due to inconsistent moisture content and burning values of different types of firewood. After the first cooking task, the mrama was used up, therefore, during the second CCT we used the mtema. The team conducting the CCT had stocked the firewood in advance. The moisture content of the firewood used was measured two weeks before our first CCT in January 2016. Rajabu (2016) determined the moisture content of the firewood to be 15%. The firewood used during the CCT was stored in a dry and sheltered place in order to maintain a similar moisture content.

In order to simulate the range of different household sizes, we grouped them within the cooking tasks. Three groups were provided with different amounts of food to be cooked. We simulated a small sized household of two to three members (household size S), a medium sized household of four to five members (household size M), and a large sized household of six to seven members (household size L).

The assessment was divided into three different cooking tasks (cooking tasks 1, 2, and 3).

Cooking tasks 1 and 2 were conducted during the first CCT in January 2016 in order to identify performance differences between TSF stoves and the initial ICSs. Cooking task 3 was conducted during the second CCT in February 2016. The focus of the second CCT was to determine whether the design shift from the initial to the modified ICS resulted in significant differences regarding firewood and time consumption during cooking. The test groups were divided into initial ICS and modified ICS. The category of initial ICS included the initial ICS users and early adopters. The category of modified ICS users included those who adopted the technology six months after the introduction of the initial ICS following the stove design described in table 1.

Cooking task 1/meal 1: rice and vegetables (fast cooking food)

A total of 20 households were asked to cook rice and vegetables on the different stove types, resulting in 40 cooking tasks. For the analysis, we used 38 test samples; two were rejected due to measurement errors.

Household size S cooked 500 grams (g) of rice and 550 g of vegetables (tomatoes, onions, and cabbage). In total, five test samples with TSF stoves and five test samples with the initial ICS were conducted. Household size M cooked 1000 g of rice and 550 g of vegetables. In total, seven test samples with TSF stoves and eight test samples with the initial ICS were conducted. Household size L cooked 1500 g of rice and 550 g of vegetables. In total, seven test samples with TSF stoves and six test samples with the initial ICS were conducted.

Cooking task 2/meal 2: beans and rice (slow cooking food)

Beans require simmering until they soften, often up to 2 or 3 hours. In total, 20 households conducted this cooking task. One was dropped due to data inconsistency. The results of 19 households (38 test samples) were used in this analysis.

Household size S cooked 250 g of beans and 500 g of rice. In total, 10 test samples were conducted: five using TSF stoves and five using the initial ICS. Household size M cooked 500 g of beans and 1000 g of rice. In total, 17 test samples were conducted: eight with TSF stoves and nine with the initial ICS. Household size L cooked 750 g of beans and 1500 g of rice. In total, 11 test samples were conducted: six using TSF stoves and five using the initial ICS.

Cooking task 3/meal 3: maize flour and vegetables (very fast cooking food)

During the second CCT, 32 ICS users were monitored. Each household was monitored twice, resulting in 64 samples. Four test samples were dropped due to measurement errors.

In total, 25 test samples were collected from users of the initial ICS and 35 from modified ICS users.

During this test, three groups were formed based upon the aforementioned household sizes. Household size S received 500 g of maize flour and 550 g of vegetables to be cooked: we tested seven households with the initial ICS and ten with the modified ICS design. Household size M received 1000 g of maize flour and 550 g of vegetables: nine test results were obtained for the initial ICS and 19 for the modified ICS. Household size L received 1500 g of maize flour and 550 g of vegetables: nine test samples were gathered by using the initial ICS and six by using the modified ICS design.

Data collection and statistical analysis

The formulas applied to calculate the performance indicators of the stoves were derived from the testing protocol developed by Bailis (2004). The specific firewood consumption (SC), (equation (3)) is displayed as the grams of firewood per gram of ingredient to be cooked. It is calculated as the ratio of total firewood consumed (equation (1)) per total amount of ingredients used before cooking in grams (equation (2)). In addition to Bailis (2004), we introduced the indicator 'time spent to cook 1000 g of ingredients' in order to provide a relative indicator to display cooking time and input of ingredients (equation (4)). Using this indicator, we assume linearity between cooking time and amount of food cooked. The time spent to cook a meal is calculated in equation (5):

$$f_c = f_i - f_f \tag{1}$$

where f_i is the weight (g) of firewood at start of the cooking task and f_f is the weight (g) of the remaining firewood.

$$W = \sum_{i=1}^{n} c_i \tag{2}$$

with c_i as type of ingredient used in grams during cooking.

$$\mathrm{SC} = \frac{f_c}{W} \tag{3}$$

$$t_{\text{time spent to cook 1000 g of ingredients}} = \frac{\Delta t}{\left(\frac{W}{1000}\right)} \tag{4}$$

$$\Delta t = t_f - t_i \tag{5}$$

where total cooking time is the time in minutes between t_i when the cooking process begins and t_f when cooking process is finished.

Results

Firewood and time consumption

Following the CCT test in January and February 2016, the firewood and time consumption per meal and cooking device was analysed in order to identify the total

Table 2. Firewood and time consumption for different meals and types of stove used.

	Meal 1: rice and vegetables ($n = 38$)	Meal 2: beans and rice ($n = 38$)		Meal 3: maize flour and vegetables ($n = 60$)
Total firewood consumption				
Initial ICS (g)	1375 (SD 792)	3576 (SD 696)	Initial ICS (g)	1245 (SD 398)
TSF stove (g)	2187 (SD 879)	4241 (SD 1540)	Modified ICS (g)	1181 (SD 239)
Difference (initial ICS−TSF stoves) (g)	−812	−665	Difference (modified ICS−initial ICS) (g)	−64
Difference (initial ICS−TSF stoves) (%)	−37.1[a]	−15.6	Difference (modified ICS−initial ICS) (%)	−5.1
Total time consumption				
Initial ICS (min)	60.3 (SD 13.6)	138.8 (SD 23.1)	Initial ICS (min)	32.7 (SD 10.5)
TSF (min)	82.4 (SD 28.3)	179.7 (SD 43.3)	Modified ICS (min)	28.9 (SD 8.2)
Difference (initial ICS−TSF stoves) (min)	−22.1	−40.9	Difference (modified ICS−initial ICS) (min)	−3.8
Difference (initial ICS−TSF stoves) (%)	−26.8[a]	−22.8[a]	Difference (modified ICS−initial ICS) (%)	−11.6

[a] Significant differences at a level of significance of 0.05.

Table 3. Specific firewood consumption and time spent to cook 1000 g of ingredients for different meals and types of stove used.

Meal 1: rice and vegetables			
	TSF ($n = 19$)	Initial ICS ($n = 19$)	Modified ICS
Specific firewood consumption (g of firewood/g of ingredient)[a]	0.583 (SD 0.234)	0.384 (SD 0.182)	–
Time spent to cook 1000 g of ingredients (min)	22.91 (SD 9.24)	17.73 (SD 5.5)	–
Meal 2: beans and rice			
	TSF ($n = 19$)	Initial ICS ($n = 19$)	Modified ICS
Specific firewood consumption (g of firewood/g of ingredient)	0.663 (SD 0.208)	0.589 (SD 0.24)	–
Time spent to cook 1000 g of ingredients (min)[a]	30.75 (SD 14.19)	22.71 (SD 7.79)	–
Meal 3: maize flour and vegetables			
	TSF	Initial ICS ($n = 25$)	Modified ICS ($n = 35$)
Specific firewood consumption (g of firewood/g of ingredient)	–	0.399 (SD 0.157)	0.398 (SD 0.132)
Time spent to cook 1000 g of ingredients (min)	–	10.44 (SD 3.73)	9.45 (SD 2.81)

[a] Significant differences at a level of significance of 0.05.

firewood and time consumption patterns (table 2). The table shows the performance of all households tested, regardless the amount of food cooked. We found a significant reduction in both firewood and time for cooking task 1—rice and vegetables—between the traditional TSF stove technology and the initial ICS model. The realized firewood and time savings for cooking task 2—rice and beans—were comparably lower, but still significant for the indicator of time consumption. With cooking task 3, we found that, although not statistically significant, compared to the initial ICS model, the modified ICS saved firewood and time.

Specific firewood consumption and time spent to cook 1000 g of ingredients

In order to display firewood and cooking time relative to the amount of ingredients used, we introduced indicators for the specific firewood consumption and time spent to cook 1000 g of ingredients; displayed in table 3. For cooking task 1, 'rice and vegetables,' we found that specific firewood consumption of the initial ICS was significantly lower (34.1%) than that of TSF stoves. Initial ICSs saved around 22.6% of the time spent to cook 1000 g of ingredients compared to TSF stoves.

Cooking task 2, 'beans and rice,' needed a long simmering time in order to soften the beans. The results show that the specific firewood consumption of initial ICSs was reduced by 11.1% when compared to TSF stoves. Relative to TSF stoves, initial ICSs significantly reduced the time spent to cook 1000 g of ingredients by 26.1%.

Cooking task 3, 'maize flour and vegetables,' was designed to identify performance differences between the initial ICS and the modified ICS. The specific firewood consumption and time spent to cook 1000 g of ingredients using the initial ICS and modified ICS is comparable. Compared to the initial ICS, the modified ICS used 0.3% less firewood and 9.4% less time to cook 1000 g of ingredients (not statistically significant).

Effect of household size on TSF stoves, initial ICS, and modified ICS performance

As we aimed to cover a broader range of cooking situations we extended the standard CCT protocol with differing meals according to household sizes. In figures 3 and 4, we display the specific firewood consumption, as well as the time spent to cook 1000 g of ingredients

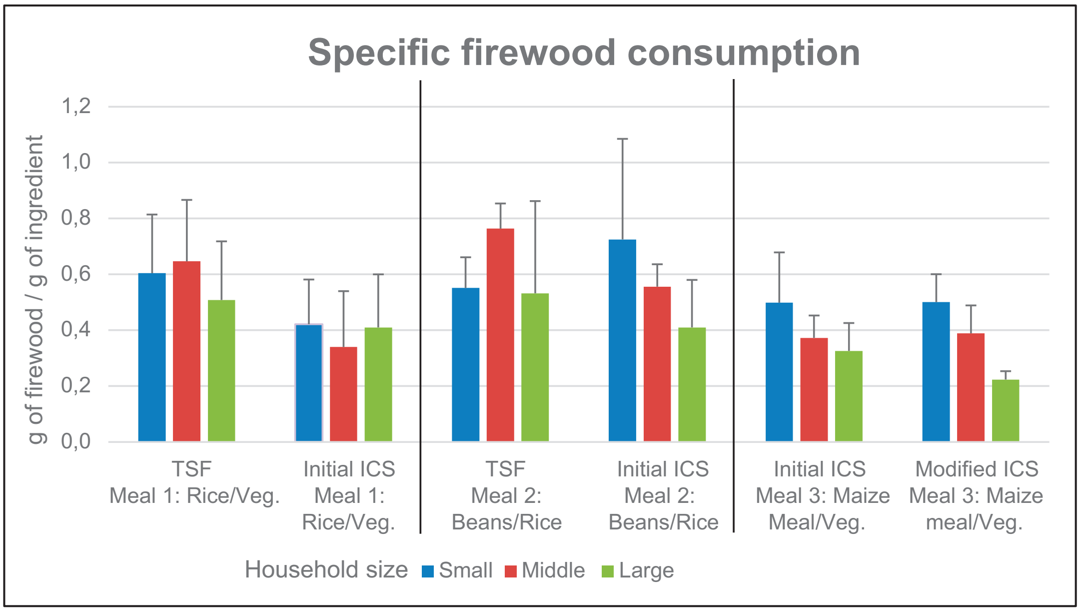

Figure 3. Specific firewood consumption for different stove technologies and household size.

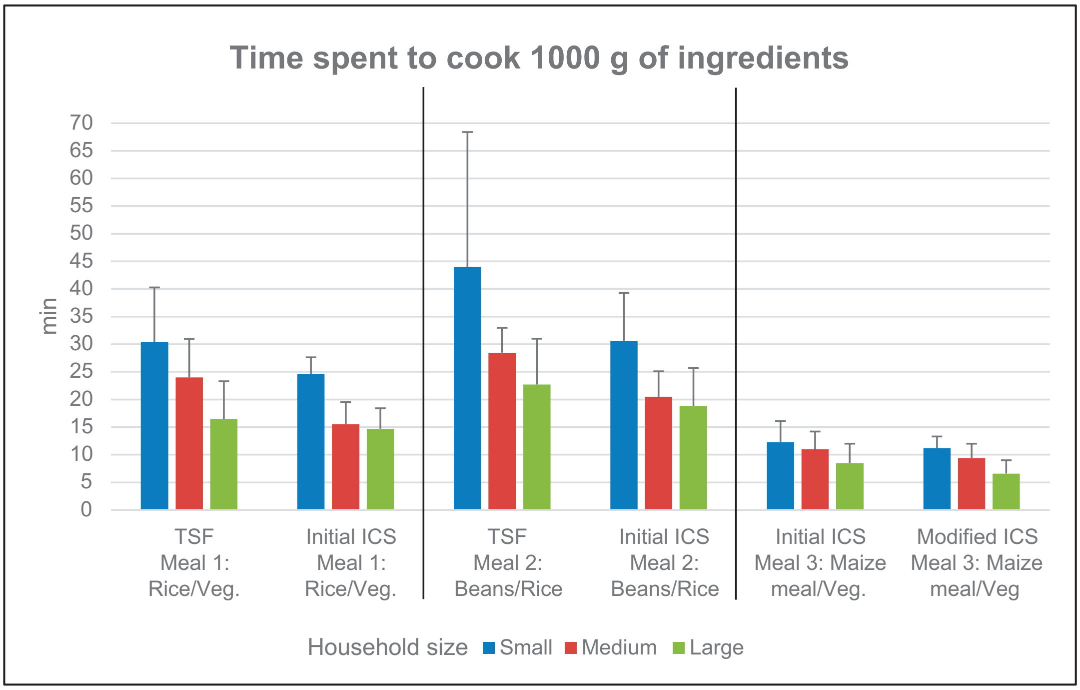

Figure 4. Time spent to cook 1000 g of ingredients for different stove technologies and household size.

based on the cooking task, household size, and cooking technology used.

In addition to the demonstrated reduction of firewood and time spent to cook a meal, the CCT test showed that all three cooking technologies—TSF stoves, the initial ICS, and the modified ICS—realized a reduction in specific firewood consumption and time spent to cook 1000 g of ingredients between small and large household sizes. The specific firewood consumption was reduced by 34.7% (55.4%) when large households were compared to small households during cooking task 3, measured with the initial (modified) ICS. Time spent to cook 1000 g of ingredients was reduced by 30.9% (41.1%) with the initial (modified) ICS when large households were compared to small households during cooking task 3.

Detailed information, including household size, number of observations per cooking task, total ingredients used, firewood consumption, total cooking time, specific firewood consumption, and time spent to cook 1000 g of ingredients, is displayed in table 4.

Table 4. Firewood and time consumption of TSF stoves, initial ICSs and modified ICSs, based on household size.

	Household size	*n*	Total ingredients used before cooking (g)	SD	Firewood consumption (g)	SD	Total cooking time (min)	SD	Specific firewood consumption (g of firewood/g of ingredient)	SD	Time spent to cook 1000 g of ingredients (min)	SD
Meal 1: rice and vegetables												
TSF	Small	5	2458	303	1485	543	74.6	27.3	0.60	0.21	30.4	9.9
	Medium	7	3689	294	2385	930	89.3	28.9	0.65	0.22	24.0	7.0
	Large	7	4992	377	2490	832	81.1	30.9	0.51	0.21	16.5	6.8
Initial ICS	Small	5	2176	114	912	332	53.6	6.7	0.42	0.16	24.6	3.0
	Medium	8	3810	266	1282	737	59.2	14.7	0.34	0.20	15.5	4.0
	Large	6	4576	360	1886	931	67.3	14.9	0.41	0.19	14.7	3.7
Meal 2: beans and rice												
	Household size	*n*	Total ingredients used before cooking (g)	SD	Firewood consumption (g)	SD	Total cooking time (min)	SD	Specific firewood consumption (g of firewood/g of ingredient)	SD	Time spent to cook 1000 g of ingredients (min)	SD
TSF	Small	5	3960	1896	2183	611	145	27	0.55	0.11	44.0	21.4
	Medium	8	6496	840	4961	851	185	39	0.76	0.09	28.5	4.5
	Large	6	9386	2251	4997	1212	200	47	0.53	0.33	22.7	8.3
Initial ICS	Small	5	4380	1295	3176	596	126	14	0.73	0.36	30.6	8.7
	Medium	9	6770	1068	3765	347	135	19	0.56	0.08	20.5	4.6
	Large	5	8864	2010	3635	1139	157	29	0.41	0.17	18.8	6.9
Meal 3: maize flour and vegetables												
	Household size	*n*	Total ingredients used before cooking (g)	SD	Firewood consumption (g)	SD	Total cooking time (min)	SD	Specific firewood consumption (g of firewood/g of ingredient)	SD	Time spent to cook 1000 g of ingredients (min)	SD
Initial ICS	Small	7	2154	357	1074	252	25.6	5.2	0.50	0.18	12.3	3.8
	Medium	9	3123	242	1164	301	34.0	9.0	0.37	0.08	11.0	3.2
	Large	9	4480	565	1460	503	36.9	12.8	0.33	0.10	8.5	3.5
Modified ICS	Small	10	2279	356	1141	187	25.6	5.4	0.50	0.10	11.2	2.1
	Medium	19	3199	337	1244	276	29.9	8.0	0.39	0.10	9.4	2.6
	Large	6	4685	558	1047	98.7	31.0	12.5	0.22	0.03	6.6	2.4

Discussion

Methodological approach

The applied research design was based on a random selection of households in Idifu. The households were selected cross-sectionally among the village households based on the primary type of stove used for cooking (Hill *et al* 2008). Although stove stacking occurred in some households, most households using ICSs removed the previous TSF cooking technology.

In order to avoid data inconsistency due to different firewood species used, we did not compare the results of the first CCT with the results of the second CCT. During the CCTs, we used local wood species. We dried the firewood before usage to ensure equal moisture content (approximately 15%). Nevertheless, firewood with deviating moisture content and distinct burning values might influence the performance of ICSs.

At the same time, the emission of harmful air pollutants might be enhanced (MacCarty *et al* 2010). The design of the ICS stove (including a chimney) creates air ventilation, which supports a draught and draws the smoke toward the chimney exit. Studies of TSF stoves and ICSs in northern India showed that ICSs contribute to the reduction of the emission of harmful gases and aerosols during cooking (Suresh *et al* 2016; Singh *et al* 2014).

The applied CCT is cited to be the best solution for simulating a cooking task in households under controlled conditions (Bailis 2004). The results of this study are compared to the results of other stove performance tests such as the Water Boiling Test (WBT) and the Kitchen Performance Test (KPT). Both tests have strengths and weaknesses but are suitable as a reference to our CCT results by demonstrating relative performance differences between TSF stoves and ICSs. The standard deviation of CCTs are typically higher than those of laboratory tests like the WBT but lower than during a KPT (Roden *et al* 2009). The KPT test is a field-based test which measures the fuel consumption at household settings using local cooks. The KPT is labour intensive and require field logistics. The KPT provides results on the daily per capita fuel consumption. The results show a higher variation than laboratory tests. However, the data might be more reliable because the measurements reflect actual household situations (Smith *et al* 2007). The WBT is a laboratory test and aims to demonstrate very reliable performance data under laboratory conditions. The WBT can be conducted with relatively minor labour and financial inputs compared to the stove performance CCT and KPT. During the WBT, water is heated to boiling point; the time to boil water, specific firewood consumption as well as the energy efficiency with high and low energy input are measured (Bailis *et al* 2007). However, the validity of the results might be limited because the assumption of laboratory conditions in actual household settings is not warranted.

During a KPT, a qualitative assessment besides the quantitative analysis is conducted (Smith *et al* 2007). A qualitative analysis is important in order to better understand the factors driving adoption, long-term usage, and scaling up of ICS technologies. While this study focused on field-based performance assessment of ICSs by using the CCT, further research using the KPT tool is recommended to better understand the factors driving the uptake of the new stove technology (Bailis *et al* 2007, Bentson *et al* 2013).

The methodology and the formulas used in this study were derived from Bailis (2004). Yet, the formulas were adjusted to site specific needs of our case study area. However, a standard test protocol for two-pot ICSs is needed in order to allow comparisons among two-pot ICS performance tests worldwide.

The indicator 'time spent to cook 1000 g of ingredients' was introduced during the study. This indicator must be interpreted carefully as there might be no linear relationship between the amount of food cooked and cooking time. However, we standardized the ingredients used and their relationship among small, middle and large households in order to guarantee a linear relationship between the ingredients used and the total time needed to cook a meal. We chose this indicator to demonstrate a decreasing time consumption per additional unit of ingredients cooked.

Stove performance: TSF stoves vs ICSs

The results of this study show that when cooking meal 1, 'rice and vegetables,' the initial ICSs used significantly less specific firewood than TSF stoves. Initial ICSs used less time to cook 1000 g of ingredients than TSF stoves. The efficiency gains of initial ICSs are related to the simultaneous use of two pots (pot A and pot B) for cooking; TSF stoves cooked the different pots consecutively.

Regarding meal 2, 'beans and rice,' which required a long simmering time, initial ICSs used less specific firewood than TSF stoves. In addition, initial ICSs used significantly less time to cook 1000 g of ingredients than TSF stoves. The time savings of initial ICSs compared to TSF stoves might be explained by better insulation and, therefore, higher thermal efficiency of initial ICSs compared to TSF stoves. A major advantage of the TSF stove is its flexibility regarding different pot sizes; the dimensions of the holes for pots are predefined for ICSs (Masera *et al* 2000). Other pot sizes do not fit inside the defined holes of ICSs. Nevertheless, it was discovered that some households used a bicycle gear rim to reduce the ICS hole size to allow cooking with smaller pots.

The results of ICS performance with regard to firewood consumption depend on the type of stove constructed (MacCarty *et al* 2010, Hoffmann *et al* 2015). Different testing protocols, different stove designs, and different site conditions result in different performance figures for ICSs (Johnson *et al* 2009, Lee and Chandler 2013). Nevertheless, the findings of this study can be compared to two-pot mud stove test results from other studies. Generally, stoves optimizing fuel efficiency are cited to use between 29% and 61% less fuelwood than TSF stoves (Jetter and Kariher 2009, Garland *et al* 2015).

MacCarty *et al* (2010) conducted a WBT with a two-pot rocket stove. The analysis showed that compared to TSF stoves, the two-pot rocket stove consumed approximately 45% less firewood.

Still *et al* (2011) cooked 5 kg of ingredients using the Uganda two-pot stove with a chimney. The design and creation of the Uganda two-pot stove is very similar to the stove design analysed in our study. The authors reported a 35.6% reduction in firewood consumption compared to TSF stoves. Our analyses showed a firewood reduction of 37.1% for cooking task 1 with ICSs compared to TSF stoves.

Depending on the stove design and the meal cooked, firewood savings might vary. Grimsby *et al* (2016) tested six different stove models with low or no firewood savings when using ICSs, compared to TSF stoves. This is in line with the findings of our cooking task 2 which realized firewood savings of 15.6% when initial ICSs were compared to TSF stoves. However, large-scale benefits, such as fuel savings induced by the ICS technology, might only be realized when the modern technology is broadly adopted (Johnson and Chiang 2015, Lewis and Pattanayak 2012).

The time consumption results for ICSs and TSF stoves are not consistently cited in the literature due to varying stove testing procedures and stove designs (Hanna *et al* 2016). Therefore, a valid comparison to other studies investigating the time savings of ICSs compared to TSF stoves is not possible.

The conclusion that ICSs lead to reduced deforestation is not warranted, as 'suppressed' firewood demand and potential alternative uses of firewood may not lead to a reduction of deforestation. More research is needed to identify the primary reasons of deforestation in Tanzania in order to estimate the impact of ICSs on deforestation.

Unintended implications of the ICS technology might include a reduction in the variety of food consumed if ICSs prove to be more suitable for certain types of food. In addition, the behaviour of cooks could change because the more efficient stoves result in additional cooking (Mwampamba *et al* 2013). Therefore, the benefits of reduced firewood consumption induced by ICSs may not necessarily result in reduced overall firewood consumption and reduced deforestation.

Effects of family size on stove efficiency

The results of the specific indicators propose that the firewood and time consumption in order to cook an additional unit of food might be reduced with increasing amounts of ingredients cooked (figures 3 and 4). The results of cooking task 3 strongly underline these findings.

Effects of stove design shift on ICS efficiency

Significant performance differences between the performance of initial ICSs and modified ICSs were not found in our study (table 3). Minor differences were detected, but these differences occur naturally within a field-based test (Bailis *et al* 2007). In order to enhance local ownership for the stove programme, a bottom-up approach was supported during ICS construction. This included the involvement of local villagers in the design and construction process of the stoves. The local knowledge of farmers—here on loam construction—was used to enhance local ownership of the locally manufactured two-pot ICSs in order to support the sustained adoption and dissemination process of the stoves. The design modifications introduced by the local artisans demonstrated their commitment to the new stove technology and their initiative to improve the performance of the initial ICS design. However, design shifts introduced by local artisans could affect public trust in the new ICS technology because users might mistrust the functionality of the 'adjusted' stoves (Bailis *et al* 2009, Simon *et al* 2014). Nevertheless, the findings of this study showed that locally designed and constructed ICSs (modified ICSs) which meet local needs realized similar performance indicators as the stoves with the initial ICS design. A reduction in quality between initial and modified ICSs was not observed.

The results of this study showed that the shift from traditional toward modern types of cooking solutions, like ICSs, might lead to direct socio-economic improvements, such as a reduction in the number of times firewood collection is required, reduced household air pollution, and income growth (Kanagawa and Nakata 2007). Instead of focusing on the promotion of alternative forms of energy, which will remain unrealistic for most rural dwellers, policy makers in Tanzania might focus on supporting the transition from TSF stoves to ICSs (Owen *et al* 2013, Maes and Verbist 2012).

Conclusions and outlook

For decades, western driven ICS designs did not meet the needs of end users and therefore, a substantial number of ICS programmes failed. As shown in this paper, locally designed and manufactured ICSs can realize significant performance improvements compared to TSF stoves. In order to boost firewood savings in an environment of severe fuel wood scarcity, it is recommended that firewood efficient ICSs are used. The study showed that the initial ICSs use significantly less firewood, and need less time for cooking, than TSF stoves. In addition, the results suggest that with increasing the amount of ingredients cooked, the amount of firewood and time needed to cook additional units of ingredients is reduced.

Further research is needed to explain the adaptation process and to identify unintended negative consequences caused by the technology shift from TSF stoves to ICSs. However, enhanced local ownership among the whole ICS value chain might not only mark the beginning of a transition toward cleaner and more efficient cooking solutions in the Dodoma region, but could be the foundation underlying a transition in cooking technology for rural dwellers in Tanzania.

Acknowledgments

Special thanks go to the Leibniz Centre for Agricultural Landscape Research (ZALF) in Müncheberg, Germany, and the World Agroforestry Center (ICRAF) in Dar es Salaam, Tanzania, for their technical and financial support within the Trans-SEC project, to conduct the research in Dodoma region, Tanzania. The Trans-SEC project is funded by the German Federal Ministry for Education and Research. Furthermore, our gratitude extends to the many scholars in Tanzania and Germany who supported the collection and processing of the data.

ORCID iDs

J Hafner https://orcid.org/0000-0003-2447-6268

References

Angelsen A and Kaimowitz D 1999 Rethinking the causes of deforestation: lessons from economic models *World Bank Res. Obser.* **14** 73–98

Bailis R 2004 Controlled Cooking Test (CCT) Version 2.0 (Household Energy and Health Programme, Shell Foundation)

Bailis R, Berrueta V, Chengappa C, Dutta K, Edwards R, Masera O, Still D and Smith K R 2007 Performance testing for monitoring improved biomass stove interventions: experiences of the household energy and health project *Energy Sust. Dev.* **11** 57–70

Bailis R, Cowan A, Berrueta V and Masera O 2009 Arresting the killer in the kitchen: the promises and pitfalls of commercializing improved cookstoves *World Dev.* **37** 1694–705

Bailis R, Drigo R, Ghilardi A and Masera O 2015 The carbon footprint of traditional woodfuels *Nat. Clim. Change* **5** 266–72

Barnes D F, Openshaw K, Smith K R and ven der Plas R 1993 The design and diffusion of improved cooking stoves *World Bank Res. Obs.* **8** 119–41

Bentson S, Still D, Thompson R and Grabow K 2013 The influence of initial fuel load on fuel to cook for batch loaded charcoal cookstoves *Energy Sust. Dev.* **17** 153–7

Blin J, Brunschwig C, Chapuis A, Changotade O, Sidibe S S, Noumi E S and Girard P 2013 Characteristics of vegetable oils for use as fuel in stationary diesel engines—towards specifications for a standard in west Africa *Renew. Sust. Energ. Rev.* **22** 580–97

Blomley T and Iddi S 2009 Participatory Forest Management in Tanzania *Report*

Bond T C, Doherty S J, Fahey D W, Forster P M, Berntsen T, DeAngelo B J, Flanner M G, Ghan S, Kärcher B and Koch D 2013 Bounding the role of black carbon in the climate system: a scientific assessment *J. Geophys. Res.: Atmos.* **118** 5380–552

Campbell B, Frost P and Byron N 1996 Miombo woodlands and their use: overview and key issues

Chhatre A and Agrawal A 2008 Forest commons and local enforcement *Proc. Natl Acad. Sci.* **105** 13286–91

Desai M A, Mehta S and Smith K R 2004 Indoor smoke from solid fuels: assessing the environmental burden of disease at national and local levels *WHO Environmental Burden of Disease Series* vol 4 (Geneva: World Health Organization)

Dherani M, Pope D, Mascarenhas M, Smith K R, Weber M and Bruce N 2008 Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis *Bull. World Health Organ.* **86** 390–98

FAO 2010 Global Forest Resources 2010 *Main Report FAO Forestry paper 163*

Garland C, Jagoe K, Wasirwa E, Nguyen R, Roth C, Patel A, Shah N, Derby E, Mitchell J and Pennise D 2015 Impacts of household energy programs on fuel consumption in Benin, Uganda, and India *Energy Sustain. Dev.* **27** 168–73

Grimsby L K, Rajabu H M and Treiber M U 2016 Multiple biomass fuels and improved cook stoves from Tanzania assessed with the water boiling test *Sust. Energy Technol. Asses.* **14** 63–73

Hanna R, Duflo E and Greenstone M 2016 Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves *Am. Econ. J. Econ. Policy* **8** 80–114

Hill R C, Griffiths W E, Lim G C and Adkins L C 2008 *Principles of Econometrics* vol 5 (Hoboken, NJ: Wiley)

Hoffmann H, Uckert G, Reif C, Müller K and Sieber S 2015 Traditional biomass energy consumption and the potential introduction of firewood efficient stoves: insights from western Tanzania *Reg. Environ. Change* **15** 1191–201

IEA 2006 *World Energy Outlook 2006* (Paris: IEA) pp 419–45

IEA 2016 *World Energy Outlook 2016 Executive Summary* (Paris: IEA)

Iiyama M, Neufeldt H, Dobie P, Njenga M, Ndegwa G and Jamnadass R 2014 The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa *Curr. Opin. Environ. Sust.* **6** 138–47

Jagger P and Shively G 2014 Land use change, fuel use and respiratory health in Uganda *Energy Policy* **67** 713–26

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

Johnson F H 1999 Burning with enthusiasm: fuelwood scarcity in Tanzania in terms of severity, impacts and remedies *Forum for Development Studies* vol 1 (London: Taylor and Francis)

Johnson M, Edwards R, Berrueta V and Masera O 2009 New approaches to performance testing of improved cookstoves *Environ. Sci. Technol.* **44** 368–74

Johnson M A and Chiang R A 2015 Quantitative stove use and ventilation guidance for behavior change strategies *J. Health Commun.* **20** 6–9

Kanagawa M and Nakata T 2007 Analysis of the energy access improvement and its socio-economic impacts in rural areas of developing countries *Ecol. Econ.* **62** 319–29

Kassenga G R 1997 Promotion of renewable energy technologies in Tanzania *Resour. Conserv. Recy.* **19** 257–63

Kees M and Feldmann L 2011 The role of donor organisations in promoting energy efficient cook stoves *Energy Policy* **39** 7595–9

Kshirsagar M P and Kalamkar V R 2014 A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design *Renew. Sust. Energy Rev.* **30** 580–603

Lee C M and Chandler C 2013 Assessing the climate impacts of cookstove projects: issues in emissions accounting *Chall. Sust.* **1** 53

Lewis J J and Pattanayak S K 2012 Who adopts improved fuels and cookstoves? A systematic review *Environ. Health Perspect.* **120** 637–45

Lim S S, Vos T, Flaxman A D, Danaei G, Shibuya K, Adair-Rohani H, AlMazroa M A, Amann M, Anderson H R and Andrews K G 2013 A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the global burden of disease study 2010 *Lancet* **380** 2224–60

MacCarty N, Still D and Ogle D 2010 Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance *Energy Sust. Dev.* **14** 161–71

Maes W H and Verbist B 2012 Increasing the sustainability of household cooking in developing countries: policy implications *Renew. Sust. Energy Rev.* **16** 4204–21

Mahoo H F, Young M D B and Mzirai O B 1999 Rainfall variability and its implications for the transferability of experimental results in the semi arid areas of Tanzania *Tanzania J. Agric. Sci.* **2** 127–40

Masera O R, Saatkamp B D and Kammen D M 2000 From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model *World Dev.* **28** 2083–103

Moffat A S 1997 Resurgent forests can be greenhouse gas sponges *Science* **277** 315–6

Msuya N, Masanja E and Temu A K 2011 Environmental burden of charcoal production and use in Dar es Salaam, Tanzania *J. Environ. Prot.* **2** 1364

Mwampamba T H, Ghilardi A, Sander K and Chaix K J 2013 Dispelling common misconceptions to improve attitudes and policy outlook on charcoal in developing countries *Energy Sust. Dev.* **17** 75–85

NAFORMA 2015 National Forest Resources Monitoring and Assessment of Tanzania Mainland Main Results *Report* (Tanzania Forest Services (TFS) Agency in collaboration with the government of Finland and Food and Agricultural Organization (FAO) of the United Nations)

Ochieng C A, Vardoulakis S and Tonne C 2013 Are rocket mud stoves associated with lower indoor carbon monoxide and personal exposure in rural Kenya? *Indoor Air* **23** 14–24

Openshaw K 2010 Biomass energy: employment generation and its contribution to poverty alleviation *Biomass Bioenergy* **34** 365–78

Owen M, van der Plas R and Sepp S 2013 Can there be energy policy in sub-Saharan Africa without biomass? *Energy Sust. Dev.* **17** 146–52

Rajabu H M 2016 *Controlled cooking test results for Salama Stove at Kilosa and Chamwino* (Dar es Salaam: University of Dar es Salaam)

Raman P, Murali J, Sakthivadivel D and Vigneswaran V S 2013 Performance evaluation of three types of forced draft cook stoves using fuel wood and coconut shell *Biomass Bioenergy* **49** 333–40

Roden C A, Bond T C, Conway S, Pinel A B O, MacCarty N and Still D 2009 Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves *Atmos. Environ.* **43** 1170–81

Sander K, Gros C and Peter C 2013 Enabling reforms: analyzing the political economy of the charcoal sector in Tanzania *Energy Sust. Dev.* **17** 116–26

Scherr S J 2004 Building opportunities for small-farm agroforestry to supply domestic wood markets in developing countries *New Vistas in Agroforestry* (Berlin: Springer) pp 357–70

Shrimali G, Slaski X, Thurber M C and Zerriffi H 2011 Improved stoves in India: a study of sustainable business models *Energy Policy* **39** 7543–56

Simon G L, Bailis R, Baumgartner J, Hyman J and Laurent A 2014 Current debates and future research needs in the clean cookstove sector *Energy Sust. Dev.* **20** 49–57

Singh S, Gupta G P, Kumar B and Kulshrestha U C 2014 Comparative study of indoor air pollution using traditional and improved cooking stoves in rural households of Northern India *Energy Sust. Dev.* **19** 1–6

Smith K R, Dutta K, Chengappa C, Gusain P P, Masera O, Berrueta V, Edwards R, Bailis R and Shields K N 2007 Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the household energy and health project *Energy Sust. Dev.* **11** 5–18

Still D, MacCarty N, Ogle D, Bond T and Bryden M 2011 *Test Results of Cook Stove Performance* (Portland, OR: Partnership for Clean Indoor Air) (www.ewb-usa.org/files/2015/05/TestResultsCookstovePerformance.pdf)

Stanistreet D, Puzzolo E, Bruce N, Pope D and Rehfuess E 2014 Factors influencing household uptake of improved solid fuel stoves in low-and middle-income countries: a qualitative systematic review *Int. J. Environ. Res. Public Health* **11** 8228–50

Suresh R, Singh V K, Malik J K, Datta A and Pal R C 2016 Evaluation of the performance of improved biomass cooking stoves with different solid biomass fuel types *Biomass Bioenergy* **95** 27–34

Troil von M 1992 *Looking for Better Life in Town: The Case of Tanzania the Rural-Urban Interface in Africa* (Uppsala: Baker and Pedersen) pp 223–37

Urmee T and Gyamfi S 2014 A review of improved cookstove technologies and programs *Renew. Sust. Energy Rev.* **33** 625–35

VITA Volunteers in technical assistance 1985 *Testing Efficiency of Wood Burning Cookstoves Report* (Arlington, VA: Volunteers in Technical Assistance)

WHO 2015 Household air pollution and health fact sheet No 292 (www.who.int/mediacentre/factsheets/fs292/en/) (Accessed: 1 December 2015)

Wiskerke W T, Dornburg V, Rubanza C D, Malimbwi R E and Faaij A P 2010 Cost/benefit analysis of biomass energy supply options for rural smallholders in the semi-arid eastern part of Shinyanga Region in Tanzania *Renew. Sust. Energy Rev.* **14** 148–65

Ylhäisi J 2003 Forest privatisation and the role of community in forests and nature protection in Tanzania *Environ. Sci. Policy* **6** 279–90

Zein-Elabdin E O 1997 Improved stoves in Sub-Saharan Africa: the case of the Sudan *Energy Econ.* **19** 465–75