Farmer innovation driven by needs and understanding: building the capacities of farmer groups for improved cooking stove construction and continued adaptation

G Uckert1,4, J Hafner1, F Graef1, H Hoffmann1, A Kimaro2, O Sererya3 and S Sieber1

1 Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany
2 World Agroforestry Centre (ICRAF), Tanzania Country Programme, Dar es Salaam, Tanzania
3 Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania
4 Author to whom any correspondence should be addressed.

Abstract
Enhancing food security is one of the main goals of subsistence farmers in Sub-Saharan Africa. This study investigates the implementation of improved loam-made cooking stoves and its contribution to coping and livelihood strategies. Controlled combustion, air as well as smoke flue, and heat insulation facilitate the more efficient fuel consumption of improved cooking stoves compared to traditional stoves—namely three stone fires. Although the majority of small-scale farmers in Sub-Saharan Africa rely on the free public good of firewood, the increasing time needed for collecting firewood implies high opportunity costs for productive members of the family. The primary outcomes for users of improved stoves are reduced fuel consumption, greater safety, saved time, and reduced smoke in the kitchen.

The paper illustrates part of the output, outcome, and impact of a participatory action research approach for implementing improved cooking stoves. Special emphasis was put on enabling the villagers to construct their stoves without external support, hence having locally manufactured stoves made of mud, bricks, and dried grass. The impact pathway of improved cooking stoves followed the training-of-trainers concept, where members of the initially established farmer groups were trained to construct stoves on their own. Special focus was given to knowledge exchange and knowledge transfer in order to increase firewood efficiency and overall satisfaction of users of improved cook stoves. Encouraging the members to further adapt the stoves enabled them to scale up the construction of improved cooked stoves into a business model and increase dissemination while creating income.

Although many important benefits, like time and knowledge gain, were identified by the farmers after adoption of the new technology, we found adoption rates differed significantly between regions.

1. Introduction

1.1. Food security and innovative strategies
Enhancing food security is the most important challenge facing subsistence farmers in Sub-Saharan Africa, including Tanzania (Abalu 2008, Ehui et al 2002, Mnenwa and Maliti 2010). Various factors interfere with food security in this region, including climate change (Müller et al 2011, Kangalawe and Lyimo 2013), changing economic systems through trade liberalization and globalization (von Braun 2007), population growth, governance factors (Riisgaard et al 2010, Gerland et al 2014), and decreasing natural production resources (Shemdoe 2011). Within the scope of food security, knowledge of the local and regional environmental and socio-economic systems is required in order to foster long-term decision-making regarding the conservation of natural resources—a knowledge also needed to create and use appropriate technologies and strategies for the changing conditions in Tanzania (Graef et al 2014, König et al 2012, Schindler et al 2016, Sieber et al 2015). To cope with these
challenges, many development and research approaches are under discussion, if not already implemented, including participatory adaptive research (Maru et al 2016, Sutherland et al 1999, Kimenye and Bombom 2009, Coulter and Onumah 2002, Graef et al 2014).

Fuelwood shortage is a challenge with two facets. Firstly, as firewood is the main source for cooking energy in rural areas, and charcoal in urban areas, unsustainable, and increasingly excessive, fuelwood extraction is contributing to deforestation and environmental degradation in Tanzania (Luoga et al 2000, Mwampamba 2007, van Beukering et al 2007, Butz 2013). Secondly, fuelwood scarcity increases the vulnerability of poor households and poverty contributes to unsustainable forest resource usage (Fasie and Grote 2013, Mnimbo et al 2015). By introducing the improved cooking stove (ICS), which efficiently combuts wood and reduces heat wastage, theoretically tree conservation is enhanced, while soil and water resources are better protected and wood cost expenditure are reduced. The firewood combustion efficiency gain of the special type of implemented mud stove was mainly derived from the ‘rocket’ function of the insulated combustion chamber, which keeps the flue gases not only as hot as possible, but also increases the speed at which these hot gases scrape against the pot surface and reach the second pot (MacCarty et al 2010, Ochieng et al 2013). By using two pots, the time used to perform cooking activities can be reduced (Adkins et al 2010, Grimsby et al 2016). The suitability of ICSs to enhance resilience is based on the traditional role of firewood collection, as this duty of women and children usually requires walking long distances for collection (Barnes et al 1994, OECD/IEA 2006, Menéndez and Curt 2013, Tabuti et al 2003, Smith et al 2014). In addition, by reducing smoke emissions, women’s health is improved (Bonjour et al 2013). As long as access to modern energy sources for cooking is unrealistic, ICS usage must be considered as a promising option to increase the sustainability of the current traditional biomass energy system (Luoga et al 2000, Mead 2005, Maes and Verbiest 2012, Iiyama et al 2014).

In this paper, we analyze implementation processes and adaptation of ICSs as a practice for securing households capacities respectively family working time. Analyses and improvements were compared to the widely used, ancient type of ‘traditional’ stone fires (TSF) (Kshirsagar and Kalamkar 2014). From a theoretical perspective, this paper further aims to identify whether aspects derived from international collaboration in research for development (R4D) have strengthened the sustainability of the implementation (Kuivanen et al 2016, Maredia et al 2014).

1.2. Design shift or improvement

Any changes or slight shifts in the design might compromise the technological functions of the stoves in ways neither foreseen nor intended. Design shifts, per se, will not be recognized as negative as long as key ICS performance indicators are achieved (reduction of smoke and firewood consumption, generation of time savings, and enhancing safety in the kitchen surrounding). Each site has unique requirements for innovation up-take, including different degrees of attitude change, modification, as well as changes to customs (cooking, firewood collection, and charcoal usage) as, ‘the domain of cooking is a very traditional one in many societies’ (Kees and Feldmann 2011). Knowledge-driven design shifts, if responding to user needs, enhance the sustainability of the innovation process and ICS uptake. Like any changes in the process of energy transition, it can serve as first step toward benefiting decision-making and identifying preferences in choice for best available stoves (Treiber et al 2015). The research objective was to test the performance and firewood combustion efficiency of stoves, as implemented and locally adjusted by local farmers. Positive or negative changes in the output were monitored and triangulated with the more general implementation program and food security indicators of the researchers.

1.3. Research questions

The theory of change was used as the framework to investigate achieved implementation objectives as well as the general impacts of our research—stimulated by the R4D literature and insight into the role of user needs to achieve positive impacts on smallholder livelihoods and food security under climate change (Maru et al 2016 and Thornton et al 2017). After installing ICSs in four case study villages, we critically assessed whether the locally introduced design changes were intentional as well as what else could be learned regarding expectations and failures during the process. We encouraged the villagers to change the initial stove design if needed. We triangulate the quantitative ICS performance analyses with self-monitoring tasks by farmers and qualitative results from focus group discussions. Hypothesis creation, generated insights, and validation from researchers were verified with help from local extension workers, farmers, and practitioners throughout the implementation process (Hoffmann et al 2007). Differing ICS technology uptake rates and differing implementation practice over time caused us to examine the driving and hindering factors of ICS dissemination, uptake, and its sustained use.

1. Hence, the first research question is related to output, more specifically ICS performance: Are design shifts in stove architecture jeopardizing firewood combustion efficiency or other functional aspects?

2. The second research question considered the outcome and the fact that our action research approach may not be a one size fits all solution: How can differences in adoption rates between the villages be explained?
Third, in accordance with the desired positive impact on livelihoods and food security, we explored pathways as to how the ICS contributed to enhancing household resilience capacities and food security.

2. Methodology

2.1. Case study sites

Our research was carried out in four villages in two climatically different regions of Tanzania. The selected villages represent a large variety of existing farming systems with differing market access, differing rain-fed cropping systems, possibly integrating livestock, and village sized between 800–1500 households (Graef et al. 2014).

The regions are: (1) the predominantly sub-humid Morogoro region (average 976 mm annual precipitation), where the food systems are more diverse, primarily based on maize, sorghum, legumes, rice, and horticulture. (2) The semi-arid Dodoma region (average 570 mm annual precipitation) is predominantly characterized by flat plains. Mahoo et al. (1999) report an increased variability in rainfall from 326 mm to 882 mm per annum. The high variability in precipitation contributes to a high variability in yields and directly affects food security (Kahimba et al. 2015). The food system is primarily based on sorghum and millet, with a strong integration of livestock (Mnenwa and Maliti 2010). The Morogoro region contains areas with different levels of sensitivity concerning food security, while those in the Dodoma region are usually characterized by more uniform, high food insecurity. In Morogoro region, around 6 886 883 ha are covered by forests, which amounts to approximately 63.6% of the region’s surface. In Dodoma region, around 4 183 192 ha of the overall surface of the region is covered with forests, approximately 32.8% of the total surface of the region (NAFORMA 2015). Forest degradation and deforestation in Dodoma region has reached an alarming extent and is still occurring very quickly. Between 1995 and 2010, the national deforestation rate was estimated to be 372 816 ha per annum (NAFORMA 2015). In the Kilosa district (Morogoro region) the firewood situation is less severe than in Dodoma Region.

Figure 2 shows the location of the four villages where stove construction was trained: Two located in the Kilosa District of Morogoro Region (Ilakala and Changarawe) and two in the Chamwino District in the Dodoma Region (Idifu and Iloilo).

2.2. Implementation strategy and participatory knowledge exchange

The implementation process introduced the theoretical functioning as well as practical knowledge of ICS construction. The provision of this information, including that of ICS efficiency, as well as its economic and environmental benefits, to community members was designed to strengthen the community and to ease diffusion and adoption (Omar Makame 2007).

The stove design was selected to achieve remarkable and visible advantages in a short time. The aim was to combine smoke reduction, higher efficiency in firewood consumption due to better insulation, and enhanced handling of cooking procedures. We used a
low-cost mud stove model from a Ugandan stove program, originally developed by the Aprovecho Research Center (MacCarty et al 2010). This model was also adopted during an EU Project in another neighboring village, ‘Chololo Eco Village,’ which is close to the case study site (CSS) in Chamwino, Dodoma region. Three women experienced in ICS construction became our trainers for the first training sessions. They gave lessons while a Swahili ICS construction manual was created to ensure provision of technological knowledge. A close and fast monitoring program was established. This enabled fast reactions to tackle challenges like (a) changes in chimney design for specific kitchen or wind exposure conditions; (b) repairing cracked stoves that were constructed with mud having a low clay content; (c) facilitating ignition during drying period of wet mud block; (d) assisting ICS groups in cases of bottlenecks in material supply e.g. by providing technology for brick construction; and, finally, (e) providing strategies for wood drying and storing.

2.3. Quantitative and qualitative stove testing

Mid-term monitoring: Quantitative data collection from the ICS groups, as well as the ‘TSF’ reference groups (14–18 households in each village), started one year after implementation in each of the four villages of Idifu, Ilolo, Changarawe, and Ilakala. Only households intensively operating the ICS at least for one month were selected. To monitor changes in firewood consumption patterns and evaluate the quality of installed stoves, researchers implemented a recording procedure to estimate the kilograms of wood consumed for cooking. The testing procedure was started by the weighting of a pile of firewood (spring scale, 0.1 kg precision). The household representative then was requested to track the number of days needed to completely consume that pile. This task was repeated five to seven times by the ICS farmer group households and by other villagers in order to facilitate comparisons with TSF performance. In sum, the repetitions covered cooking practices for a period of two to three weeks. A key informant interview was carried out regarding household specifications, energy consumption, cooking habits, firewood collection, walking distance, and stove users’ perceptions of changes.

In-depth survey: Additionally, in the village of Idifu, an in-depth kitchen performance test (KPT) survey was conducted to investigate, and collect data about, stove performance by including a span of ICS adjustments. In this study of Idifu, where most ICS were constructed, we seek to gain insights from the most active dissemination process, drawing upon a sufficiently large population for a randomized sampling. The KPT was conducted as a field–based procedure to demonstrate the effect of stove interventions on fuel consumption in the kitchens of real households. The testing in this study is seen as a proper way to understand the stove’s impact on fuel use and on household behaviors because it occurs in the homes of stove users (Lillywhite 1984, Sutar et al 2015). In total 72 stove using households (52 ICS and 20 TSF) were surveyed, covering a range of different household sizes (three clusters of small, medium, and large), three types of meals cooked (A: maize flour and vegetables; B: rice and vegetables; and C: beans and rice) and the two types of ICS (implemented and adjusted) to be compared with TSF. The clusters (S, M, L) received standardized amounts of ingredients cooked corresponding to

Figure 2. Map of Tanzania, Africa with Chamwino and Kilosa districts, including the project villages of Ilolo, Idifu, Ilakala, and Changarawe indicated. Source: Geographical Information System Unit, University of Dar es Salaam, 2016 (http://project2.zalf.de/trans/sec/public/).
household members (e.g. for rice and maize flour meal: S = 500 g, M = 1000 g and L = 1500 g). We neglected meat consumption as it is—depending on households’ income—rarely part of the diet.

The qualitative part of the KPT (a semi-structured questionnaire testing protocols) sought to understand the driving factors for households to adopt the ICS technology as well as to maintain the long-term use of it. During the qualitative part of the KPT, ICS users were asked about the benefits and challenges of the new ICS technology. The interviews were directed toward identifying habitual changes that were induced by the usage of ICS. The questions asked about multiple aspects of ICS dissemination, like the monetary aspects and the willingness to pay. Health aspects of TSF stoves and ICS were investigated. The firewood collection patterns, walking time, and frequency of firewood collection for the two stove groups were compared. Statistical analyses were carried out using SPSS (SPSS Inc. 1989, 2010).

2.4. Calculation of the average daily consumption per capita

In order to compare and validate our data from the monitoring task with in-depth results from the KPT in Idifu, we calculated the value for the average daily firewood consumption of villagers in Idifu. Starting with the specific firewood consumption data of the KPT for households cooking single meals, three factors were introduced: (1) projecting average capita consumption per household; (2) the number of meals cooked per day; and (3) a combination of meals considered to be the common diet.

Based on the KPT results, the firewood consumption per capita and meal for a medium sized household ($f_{cm}$) is a calculated by the factor of 4.5. The factor is based on the average household size found in the own Baseline Household Survey and on official statistics of Chamwino District, Dodoma Region (NBS 2013):

$$f_{cm} \text{ per capita and meal} = \left( f_i - f_f \right) / 4.5 \tag{1}$$

with $f_i$ being the weight (g) of firewood at start and $f_f$ is the weight (g) of firewood after finishing the KPT cooking task.

Information on the daily frequency of cooking in Idifu, Dodoma Region, was collected from 64 households. On average, households claim to cook 2.3 times per day (SD 0.47). Hence, in order to calculate firewood consumption per capita and per day ($f_{cm}$), the above calculated figures must be multiplied by the numbers of cooking processes per day:

$$f_{cm} \text{ per capita and day} = \left( f_i - f_f \right) / 4.5 \times 2.34 \tag{2}$$

In a focus group discussion (FGD) in Idifu village, 16 participants were asked about their cooking habits, diets, and types of meals cooked during a period of time. The respondents claimed that around 80% of the meals cooked consisted of maize flour and vegetables (meal A), 15% of the meals consist of rice and vegetables (meal B), and around 5% of the meals consist of beans and rice (meal C).

$$f_{et} \text{ per capita and day} = \left( f_i, \text{meal A} - f_f, \text{meal A} \right) \times 0.8 + \left( f_i, \text{meal B} - f_f, \text{meal B} \right) \times 0.15 + \left( f_i, \text{meal C} - f_f, \text{meal C} \right) \times 0.05 / 4.5 \times 2.34 \tag{3}$$

The firewood consumption per capita and day for the common dish combination ($f_{et}$) was summed up from the weighted average of the different types of meals.

3. Results

3.1. ICS dissemination as precondition for perpetuated knowledge exchange

Between February 2015, when ICS implementation started, and December 2016, a total of 347 ICSs were constructed across the four case study sites (table 1).

The project initiated a process where the goal was to build stoves in each of the four villages constantly. However, construction was not consistent across the villages. The average monthly construction rate ranged from 3 to 15. The villages located in the semi-arid region had a consistently higher speed than those in the sub-humid region. In Idifu, we found the performance of the group to be five times higher than in Ilakala or Changarawe. The latter group almost stopped activity after having supplied all group members with improved stoves. We found that differing dissemination coincided with differing challenges. During monitoring and evaluation visits, several reasons for not constructing were named by group members. In all four villages, ICS construction essentially paused during planting season due to the workload of other farm activities. Other hindering factors inhibiting or slowing down dissemination were the floods (Changarawe), the absence of huts for building the stove (Changarawe, Ilakala), a lack of liquidity among the adopters (Ilolo, all), and the intervention of other NGO projects that built stoves free of charge (Idifu, Ilakala). The ICSs investigated here were offered at a construction fee of about $1 and customers had to contribute labor and materials.

3.2. ICS implementation and design change

The question was raised in Idifu if there is a difference in the performance of ‘originally implemented ICS’ and ‘newly adapted ICS.’ During the training phase of the ICS program, special emphasis was put on enabling the villagers to construct the stoves without support from external sources and they were encouraged to look for possible adjustments to fulfill their needs. Based on their own experiences during continued construction, artisans started modifying the stove dimensions in order to improve its performance and appearance. Changes were first observed six months after the introduction. In table 2 and figure 3, the differences of stove
Table 1. ICS dissemination in the project villages of Trans-SEC, February 2015–December 2016.

| Village name | ICS group members | January 2015–April 2016 adopters | May–August 2016 adopters | September–December 2016 adopters | Total |
|--------------|-----------------|---------------------------------|------------------------|-------------------------------|-------|
| Ilolo        | 25              | 38                              | 20                     | 7                             | 90    |
| Idfiu        | 23              | 80                              | 36                     | 38                            | 177   |
| Changarawe   | 35              | 0                               | 5                      | 1                             | 32    |
| Ilakala      | 15              | 17                              | 6                      | 10                            | 48    |
| Total        | 98              | 135                             | 67                     | 56                            | 347   |

* Flooding destroyed nine stoves in Changarawe in April 2016.

Table 2. ‘Implemented’ vs. ‘adjusted’ ICSs: difference of stove design, Idfiu village.

| Type of ICS in cm | Old ‘implemented’ ICS (N= 25) median/mean (SD) | New ‘adjusted’ ICS (N= 35) median/mean (SD) |
|------------------|-----------------------------------------------|---------------------------------------------|
| Stove height     | 42.0/43.3 (8.0)                               | 30.0/30.5 (2.3)                             |
| Stove length     | 120/115 (23.0)                                | 99.5/98.6 (11.3)                            |
| Stove width      | 56.5/56.9 (4.6)                               | 49.0/48.8 (5.2)                             |
| Diameter of the wood entry slot | 14.5/12.9 (2.6) | 15.0/14.2 (2.4) |
| Height of the combustion chamber (first pot) | 27.0/26.2 (5.8) | 18.0/19.3 (3.9) |

* Significant differences (p < 0.05) between ‘old’ implemented and ‘new’ adjusted ICS, Mann–Whitney U-test.

**Figure 3.** ICS implemented during training (left, original make) and ICS after one year of construction practice (3 × right, modified).

dimensions between the ‘old’ and ‘new’ types of ICS are displayed.

All stove design changes were significant (Mann–Whitney U-test). The ICS adjustments led to reduced height, corresponding to a reduced average distance between the bottom of the combustion chamber and the bottom of the first pot. Although the stove’s length and width dimensions were reduced, the diameter of the wood entry slot was increased. Frequently, but not regularly, we found stoves that used a diagonal connection channel between pothole one and pothole two.

3.3. Firewood situation and time burden

In our study, we approximated the change in household energy availability by examining firewood collection efforts. To distinguish between changes of availability of firewood at the collection sites from efforts depending on the distance of households to forest or bush areas, we asked separately about the time spent for the round trip and about the time spent collecting. To determine the changes in collection burdens, we asked about the age of collectors and the weight of headloads. Figure 4 displays data from the CSS villages.

On average, we found household members (both women and men) averaged around 40 years of age, carrying firewood headloads of 30–35 kg. In the villages of Chamwino District, the headload weight was higher and the collection time was doubled compared to Kilosa. It is notable that the amount of the headload increases in accordance with higher time efforts: Analyses of disaggregated data showed an upward gradient with a slight correlation between weight of headload and time to collect, even within the villages ($R^2 = 0.1337$, Kilosa).

3.4. Stove performance in villages of both CSS

Figure 5 displays the findings from the monitoring tasks of stove performance in firewood consumption per capita and day in four villages.

In the villages of Chamwino, energy consumption for cooking was significantly lower than in those of Kilosa ($p < 0.001$). In Chamwino, the wood fuel energy used for TSF was about 1 kg per capita and day, while the ICS consumed about 20% less. In Kilosa, TSF consumed about twice as much firewood: more than 2 kg (up to 2.5 kg) per day and capita for TSF, generating ICS savings of more than 50%.

To allow comparison of firewood consumption data between in-depth analyses of KPT data in Chamwino with the monitoring results across the regions, we calculated the values according to above explained procedure (equations (1) to (3)). Table 3 shows the data used for validation.

Based on the implemented ICS, the firewood consumption per capita and day for the common
Figure 4. Firewood collection indicators for Kilosa (ICS: N = 32; TSF: N = 31) and Chamwino (ICS: N = 37; TSF: N = 30): age, weight of headload; time spent to reach (round trip) and to collect at site (mean, SD).

Figure 5. Monitoring of stove performance in Chamwino and Kilosa district. Firewood consumption in [kg per capita and day], testing of daily cooking tasks of households in a period of five to seven repetitions, each period covered 3–6 d.

Table 3. Cooking with ICS: average daily per capita firewood consumption in [grams] of villagers in Idifu to be calculated as sum of meals in the diet (\(f_{ct}\)).

| Type of ICS | N     | Firewood consumption \((f_i - f_f)\) | SD | Per household member \((f_{cm})\) | Whole day \((f_{cm})\) | Share diet | Diet share per day \((f_{ct})\) |
|-------------|-------|--------------------------------------|----|----------------------------------|-----------------------|------------|-----------------------------|
| Meal A: Maize flour and vegetables implemented | 25    | 1245                                 | 398| 277                              | 647                   | 80         | 518                         |
|             | adjusted | 35                                 | 1181| 239                              | 262                   | 614        | 80                         | 491          |
| Meal B: Rice and vegetables implemented | 38    | 1375                                 | 792| 306                              | 715                   | 15         | 107                         |
| Meal C: Beans and rice implemented | 38    | 2576                                 | 696| 572                              | 1340                  | 5          | 67                          |

dish combination \((f_{ct})\) was determined to be 692 g per day; projected to be 253 kg per year and capita. This finding from KPT corresponds with the consumption level of households found within the monitoring task in Idifu (ICS: mean 0.8 kg per capita and day; SD 0.5). Cooking the most frequent dish, the adjusted ICS shows slightly reduced firewood consumption.
Table 4. Annual time savings in hours (walks) and reduction of frequency to collect firewood per household induced by ICSs in Idifu.

|                          | ICS  | TSF  | Difference |
|--------------------------|------|------|------------|
| Annual time spent to collect firewood | 149 (35) | 219 (47) | 70 (14) |
| Annual time spent for cooking | 573  | 716  | 143        |
| Annual total consumption  | 722  | 935  | 213        |

The displayed time savings induced by ICS are calculated based on data from Idifu village.

a Self-monitoring task data.
b KPT.

Additionally, we cross-checked these results of KPT with those of an independent stove testing team from the University of Dar es Salaam lead by Dr Rajabu. Implementing a controlled cooking testing protocol in our case study villages in both regions of Dodoma and Morogoro, it was found that the specific firewood consumption of ICS compared to TSF stoves is reduced by 55% in the Morogoro region and about 33% in the Dodoma region (0.05 level of significance) (Rajabu 2016). The test was standardized with rice cooked in only one pot to eliminate different cooking procedures between ICS and TSF. In Morogoro, no significant improvements on cooking time for ICS compared to TSF were found, while in Dodoma it was found that ICS took 8% more cooking time compared to TSF stoves to complete the same cooking task.

3.5. Time savings during collection of firewood and during cooking

Time savings due to ICS implementation occurred in relation to firewood collection as well as to cooking; especially due to the usage of a second pothole. We calculated the time savings in firewood collection based on the firewood consumption data. Using the originally implemented ICS led to time savings compared to TSF, mainly induced by parallel cooking with the second pothole. To highlight the impact of ICS implementation on workload and time burdens, in table 4 we display the calculation of the time saved during the cooking process with an ICS based on the in-depth data from the KPT. Cooking time for ugali and vegetables (meal A) was measured to be 30.3 min (SD 9.4 min), for rice and vegetables (meal B) 60.3 min (SD 13.6 min), and for beans and rice (meal C) 138.8 min (SD 23.1 min).

In table 4, the time savings from the reduced frequency of firewood collection as well as those induced by reduced cooking time resulting from using ICS instead of TSF are displayed.

According to consumption data displayed in figure 5 and in table 4, each year, on average 1149 kg of firewood are consumed by the average household (family size 4.5) in Idifu, if cooking with ICS. With an average headload carried of 35 kg (see figure 4), this results in 33 walks to the forest per annum, multiplied by the average time spent to collect firewood (273 min) within the ICS group and divided by 60 (factor for minutes). As a result, in households using ICS, annually, 149 h are spent collecting firewood for cooking purposes only. For TSF, calculations indicate an annual need for 1642 kg of firewood for cooking purposes; a total of 47 walks to the forest. Due to the time spent for a single trip (280 min), an average household spends 219 h collecting firewood to cook on a TSF each year. In single cases, if wood is derived from stronger branches (diameters of 8 cm and higher) or even from tree trunks, we found the task of firewood resizing in ICS households. We measured an additional time of 3.4 min (SD 1.8 min.; N = 64, 70% did chopping) to complete the cooking task.

The calculation in table 4 is based on a standard diet in Idifu (share of diet; table 3). This results in an annual time spent cooking with an ICS of 573 h (0.8 × 2.34 × 30.3 min × 365 d + 0.5 × 2.34 × 60.3 min × 365 d + 0.05 × 2.34 × 138.8 × 365 d). For comparison, based on KPT survey results, total cooking time was reduced an average of 25% when using ICS instead of TSF. Accordingly, annually 143 h are saved by cooking with ICS instead of TSF. In Idifu a total of 213 h, per household and year, can be saved if ICS are used instead of TSF (table 4): 70 h spent collecting firewood and 143 h on cooking. In the other CSS villages of Ilolo, Changarawe and Ilakala, the time savings induced by ICS vary, but time expenditures are reduced by 30%, 48%, and 30%, respectively, if ICS are used instead of TSF.

3.6. Stove adaptation incorporates merits and demerits of both stove technologies

The KPT’s qualitative analysis of ICS and TSF users in the village of Idifu—where stove dissemination was the greatest of all four CSS—helped understand the behavioral changes, utilization patterns, as well as the motivation behind the ICS design change and adaptation. Among ICS users, 90% of the households claimed that they used the ICS technology throughout the year. Two households stated that they could not use the ICS during strong winds and heavy rains.

The perceived changes with regard to smoke emissions were substantial. ICS users claimed that household air pollution during cooking was highly reduced with ICS compared to TSF. With respect to cooking habits, all households stated that there were no restrictions on meals cooked. The ICS design did not prevent meals from being cooked and did not influence the diet of the users negatively. The ICS was considered beneficial not just because 90% of the households claimed to cook faster with ICS than with TSF, but because 85% of households reported needing less time to collect firewood. The time saved was used for other activities, including farm work or housework. About 25% of the households reported purchasing part or all of their firewood from vendors.

These results derived from KTP in Idifu are consistent with the monitoring and evaluation task in all.
four CSS villages. Here, villagers perceived the obvious reduction in the amount of firewood used for ICS versus TSF as a main advantage. A high reduction in the amount of smoke of ICS in relation to TSF in the kitchen was also stated. The villagers found that the general performance of ICS compared to TSF is high: it cooked faster and was very simple to use. They also appreciated that temperature in the kitchen was lower than before.

3.7. Non-adoption of TSF stove users
During the in-depth qualitative questionnaire in Idifu, TSF users were asked about the reasons for not adopting the ICS technology. About 30% of households stated that they were not aware of the advantages and the overall handling of ICS, while 25% of households claimed that their homes were not spacious enough to construct an ICS. Additionally, 20% of households mentioned that they lacked the financial means or input materials (e.g. bricks) needed for adopting the ICS technology. Only one household responded that they did not want to change the cooking technology because of the traditional usage of TSF stoves in the village.

When asked about health-related issues resulting from using TSF, 85% of the households mentioned problems, such as respiratory diseases as well as eye and mucous membrane infections.

4. Discussion

The main drivers for ICS adoption were found in scarcity and awareness of limited natural resources, smoke reduction, as well as the time saved in collecting and cooking. An important pull factor was found in the role of the established farmer groups that facilitated the ICS construction learning process, along with a close accompaniment of farmers by participatory research processes during the first phase of the implementation. While initially income and education seem to be the driving factors for adopting a new technology, its long-term use can be traced back to cultural reasons (Troncoso et al 2007). The success of an ICS program may also depend on associated perspectives that are either people- or technology-centered (Troncoso et al 2011): we found social aspects and positive recognition of neighbors to be very important. However, a high dissemination rate is vital for the long-term usage of new technology and a crucial indicator determining a program’s success (Sinton et al 2004, Rehfuess et al 2014).

4.1. Comparison of regions in implementation and dissemination
To explain the differences in the implementation success of ICS between the regions, we consider the availability of firewood for cooking and its impact on changing behaviors. Is high scarcity the only driver leading to a change in cooking habits? First, the significantly lower firewood consumption for cooking in the semi-arid region of Dodoma compared to Morogoro (figure 5) was found to be an indication of severe firewood scarcity. Secondly, the long walking distance and increasing time to gather a headload of firewood in the area for collection (figure 4) indicated the high pressure on natural and forest reserves. On the basis of the results regarding round trip distances and searching time, we suggest the hypothesis that ongoing unsuccessful searching for, and gathering of, firewood is triggering awareness. This resulted in enhanced efforts in ICS construction and improvements, sharing techniques for gathering (ox carts), drying, and storing of firewood, as well as knowledge on environmental conservation in this region where stocks were depleted. The high awareness of scarcity is likely to be mirrored by the fast spreading of ICS technology.

Firewood availability in Morogoro region is less severe, with less labour and other resources allocated to the construction and dissemination of ICS. From the villager’s perspective, issues like smoke reduction, increased free time and comfort, as well as higher security for small children gain importance.

Differences in the environment between the two climatically different sites (semi-arid and sub-humid) explain our variation in firewood consumption patterns, as also stated by Biran et al (2004). In 1983, women were described as carrying an average of 20–30 kg per headload of firewood in Dodoma (Skutch 1983). This weight increased sharply in the last decades, as our 2016 results show (see figure 4). Increased distances and collection times have already resulted headloads reaching up to 35 kg. Such heavy loads may explain why the task is carried out by working aged family members. Accordingly, the task of collection competes with other labor tasks. As farming is the most urgent task during the rainy season, we found that firewood collection in the semi-arid region is already commonly shifted to the dry season. This coping practice leads to extensive firewood storage, with the positive effect of sufficient wood drying, which is, in turn, a critical precondition for clean combustion in ICS.

At regional and local levels, we can identify specific determinants that affect up-take and dissemination of ICS. Awareness for environmental pressure and the perception of firewood scarcity: under the semi-arid conditions in the Dodoma Region, the obvious projection of high and rising pressure in the future boosted awareness of scarcity, which become a motivation. Time spent collecting firewood was between three and a half to four and a half hours. Although time expenditures in Chawino CSS villages are just about 40 min, the rate of ICS adoption is three to four times higher there than in Kilosa CSS villages. In the sub-humid region of Morogoro Region, especially in Changarawe—with a low distance to Kilosa Town, the capital of the district—we found that the population tends to be more reserved about adopting
the mud type ICS. However, we recognized different adoption speeds when starting stove construction for the rest of the villagers. The low rates among farmers in Changarawe might be explained by the uncertainty of property rights, as they were settled on governmental land after shifting their old village from hills to plains. Therefore, floods can harm the kitchen and permanent stoves can be destroyed, which limits the dissemination strategies of this type of ICS. However, interventions were affected by reciprocal actions of villagers and stove extension workers. The group in Changarawe was almost passive, acting very slowly in constructing and disseminating the one mud type. We now suggest that portable stoves are a better solution in areas prone to flooding.

The perception of ICS users in Idifu is that population growth and human habitat enlargement are the major reasons for the ongoing deforestation, along with uncontrolled charcoal production and livestock keeping. In addition to rapid population growth, indirect drivers concomitant with degradation are poverty and unsecure land tenure (URT 1999). A long-term goal should be increasing sustainability by balancing firewood collection with the re-growth rates of wood sources. With growing populations, the ICS contributes to stabilizing the demand for solid biofuels in the rural communities in poverty, an issue of high importance in the medium-term before modern energy can potentially take over (Brew-Hammond 2010, Hoffmann et al 2015, Johnson and Bryden 2012, Kaygusuz 2011, Owen et al 2013).

4.2. Type of meals and cooking habits determine height of firewood savings
To reduce firewood consumption, it was found that coping strategies had already affected cooking habits in the region with a high firewood scarcity: the first was to skip one meal per day in order to reduce the number of cooking tasks. Second was that 80% of meals consisted of the fastest cooking dish (maize flour). Third was seen in the 5% share of cooked beans dishes, corresponding to a frequency of once per week (if cooking about 2.3 times per day). Severe firewood scarcity resulted in a change of cooking habits. Households that were aware of saving potentials could easily facilitate the quick adoption of ICS. The frequent construction practice would contribute to the creation of user friendly ICS in the next step, thus enabling broader usage of the stove. Food security is a function of the amount and quality of food, as well as the frequency of being served (FAO 2004). To improve food security, a higher diversity of meals, derived by agrobiodiversity and nutritious food systems, should be aimed for, as unbalanced diets often lack essential nutrients (Graham et al 2007, Welch and Graham 1999). Firewood scarcity is a factor hindering the preparation of diverse meals; especially those demanding large amounts of firewood; e.g. for long simmering of beans. We found that households where the cooks soaked their beans in water for some hours, used less than half of the firewood that other cooks needed to cook beans.

4.3. Design shifts and technology efficiency
Participative ICS implementation by farmer groups and local trainers enabled a process of design changes. This led to the stove being adapted to local needs, which led to wider adoption. For example, the shorter stoves not only led to increased heat transfer for the second pot, but it also contributed to a reduction in material inputs. Ilakala highlights how the adoptions benefit local construction: due to poor proper soil availability, they had to carry four bags of clay to the stove construction site in order to construct the originally designed ICS. Reducing the height of the fire chamber implies that less material is needed, but also might lead to refuse part of the rocket stove principle. Ergonomically, the observed height reduction aligns to the customary sitting position for cooking, meaning that usage is more like the TSF. Unfortunately, a transition from highly-polluting stoves to cleaner burning ICS often results in shifting pollution to neighboring homes (Simon et al 2014). Thus, it is important that the rocket type stove supports clean combustion—mainly achieved by enabling a flow with sufficient long duration of fuel gases in the heat of the fire chamber. If the flow passage of fuel gas is too short or temperature too low, then complete combustion might not be ensured. Irrespective of the rocket pipe and its defined dimensions (Adkins et al 2010, MacCarty et al 2010, Ochieng et al 2013), in training we encouraged ICS users to carefully record any changes in the amount of char residues and the particles coming out of the chimney after establishing design changes into further developments. Both remaining char and emitted smoke (visible particles) would indicate the loss of firewood combustion efficiency in the main fire chamber. Analyses of the kitchen performance test showed that both types of ICS achieve similar firewood combustion efficiency. To understand all impacts of the design shifts, we take into account that the iterative changes cut down the distance to the second pothole. Consequently, there was improved firewood combustion efficiency, if looking at the whole stove performance measured in the KPT. Unknown amplitudes of simultaneous effects that are not necessarily commutated indicate that more research is needed regarding the two-pothole-type stove adjustments. However, overall, adjustments are seen as user friendly if they improved the handling of cooking. Moreover, the self-determined continuous changes are assumed to increase the ownership by the villagers and support further engagement with ICS technology (Omar Makame 2007). Nevertheless, all adjustments must be carefully checked and require continuous monitoring of quantitative emissions and qualitative standards. We suggest instituting some form of professional education for stove builders, thus ensuring that the built ICS stoves meet quality standards.
4.4. Stakeholder participation and change

Most positive changes due to the implementation of ICS were well understood, but households are in charge of implementation success and had to overcome common initial hindering factors (Barnes et al 1994), like housing requirements—e.g. a roof is needed to protect mud ICS against rain, while the kitchen has to be spacious, and there is more effort needed for firewood preparation. Chopping wood into sizes that fit into the smaller entrance of the fire chamber reduces the time savings due to ICS usage. From the perspective of a sustainable produce and usage of wood for cooking, smaller sticks should be promoted. The small sized sticks could preferably be derived from branch cuttings (regrowth), while also allowing for improved heat control.

The theory of change defines the role of research to enable additional output within the development task (Thornton et al 2017). The people centered approach of action research organizes the process of innovation adoption toward the needs of evidence based knowledge dissemination (Gaziulusoy et al 2016, Graef et al 2014). This is in line with the need of farmers for fast success and increasing profit in order to improve their livelihoods. Although entrepreneurship is at a low level in the CSS, we installed mechanisms of knowledge exchange that sought to encourage and support the propensity for experimentation, risk-taking, and for trying new things (Maru et al 2016, Barrett et al 2017, Gaziulusoy et al 2016, Graef et al 2014).

The successful implementation and dissemination was based on strong stakeholder participation within FGD and training sessions, as well as on the feedback loops derived by quantitative and qualitative results of the continued process of monitoring. However, farmers co-operating with scientists in action research creates challenges: due to imposing an unbiased sample resulting in a high share of villagers unfamiliar with innovation processes, we found that expectations among farmer group members were sometimes unrealistic. The collaboration of local researchers and farmers must be evaluated with respect to its ability to create impact and encourage adoption (Neef and Neubert 2011, Vandermeulen and Van Huylenbroeck 2008).

Here, knowledge exchange within the farmer groups was reinforced by the continuous support of local extension workers as well as masters’ students accompanied by the work of international researchers looking for evidence based results. This enabled all involved stakeholders to identify potential drivers, additional needs, and bottlenecks at the moment in time when the ICS constructors and users needed it most. Accordingly, knowledge exchange and internal knowledge systems were key factors facilitating capacity building. However, a crucial incentive for stove construction is a quick profit. Therefore, the mutual agreement on a fixed, but low (pro-poor), ‘selling price’ for ICS stoves (about $1–1.5 as compensation for expenses of trainers)—instead of a supplement of subsidized products at no cost—contributed to the ownership of the stove users and encourage further usage.

5. Conclusion and the way forward

The study concludes that the implementation of ICS technology substantially improves livelihoods due to greater firewood combustion efficiency, reduced perceived smoke, and time savings. Reduced time for cooking and firewood collection leads to a time gain that can be alternatively used for crop production or educational activities for children.

The key link is the correlation between increased knowledge exchange on stove application and the construction after implementation of trainer groups. Differences in dissemination performance suggest that there is not a generalizable standard solution for introducing ICSs. The implemented two-pothole mud type ICS using firewood is well adjusted for pro-poor conditions in remote areas, where scarce firewood is the main source of cooking energy.

From the user perspective, adjustments to the ICS were recommended with an eye toward improving the performance of the second pothole. Further adjustments may introduce a third pothole, may invent pottery inlays for charcoal fillings, or may adjust the stove dimensions for bigger pots. Establishing capacities on stove construction and design adaptations are critical for continuous and sustainable stove dissemination, until the project fades out. Trainers could gain confidence of stove users and all of those exposed to their outputs if they were supported through a kind of apprenticeship or ongoing knowledge exchange programs.

These findings are in line with the Tanzanian policy initiative, supporting site-specific and needs-based tailored solutions depending on the local and regional conditions at socio-economic and bio-physical levels.

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ORCID iDs

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