*Article*

# Fuelwood Savings and Carbon Emission Reductions by the Use of Improved Cooking Stoves in an Afromontane Forest, Ethiopia

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**Abstract:** In many Sub-Saharan African countries, fuelwood collection is among the most important drivers of deforestation and particularly forest degradation. In a detailed field study in the Kafa region of southern Ethiopia, we assessed the potential of efficient cooking stoves to mitigate the negative impacts of fuelwood harvesting on forests. Eleven thousand improved cooking stoves (ICS), specifically designed for baking Ethiopia's staple food *injera*, referred to locally as "*Mirt*" stoves, have been distributed here. We found a high acceptance rate of the stove. One hundred forty interviews, including users and non-users of the ICS, revealed fuelwood savings of nearly 40% in *injera* preparation compared to the traditional three-stone fire, leading to a total annual savings of 1.28 tons of fuelwood per household. Considering the approximated share of fuelwood from unsustainable sources, these savings translate to 11,800 tons of $CO_2$ saved for 11,156 disseminated ICS, corresponding to the amount of carbon stored in over 30 ha of local forest. We further found that stove efficiency increased with longer *injera* baking sessions, which shows a way of optimizing fuelwood savings by adapted usage of ICS. Our study confirms that efficient cooking stoves, if well adapted to the local cooking habits, can make

a significant contribution to the conservation of forests and the avoidance of carbon emission from forest clearing and degradation.

## 1. Introduction

Deforestation and degradation of forests constitute the most important sources of greenhouse gas emissions in many developing countries, particularly in Sub-Saharan Africa [1]. At the same time, energy from fuelwood is essential to sustain livelihoods in this region [2,3]. Fuelwood collection for cooking is a main driver of forest degradation in these countries [4], though this phenomenon is difficult to quantify, even with sophisticated methods, like remote sensing [5]. At the same time, indoor air pollution caused by traditional cooking constitutes a major health risk [6]. Therefore, strategies to reduce fuelwood consumption have the potential of simultaneously mitigating climate change, conserving forests and improving human livelihoods.

In Ethiopia, the pressure on forests is particularly high, due to expansion of agriculture and other large-scale investment programs [7]. In a long-term perspective, deforestation in Ethiopia has been steadily increasing at alarming rates. According to FAO estimates [8], the total area of natural forests in 1990 was 15.1 million ha and was reduced within 20 years to 12.3 million ha. Accordingly, Ethiopia has lost 140,000 ha natural forest annually, and fuelwood collection played an important role in the process [8–10]. A study from Ethiopia, which considered regrowth, harvesting of fuelwood and fuelwood consumption, revealed that on a local scale the harvest is three-times the annual allowable cut [11].

Alternatives to fuelwood as cooking fuel are generally expensive and hardly available in Sub-Saharan Africa. As a result, the demand for fuelwood in rural communities remains inelastic as long as the resource continues to be available to these communities [12]. Investments in direct fuel saving solutions are thus needed to combat the unsustainable use of fuelwood. An important strategy is the distribution of improved cooking stoves (ICS) [12–14] that allow for significant savings of fuelwood without the need to introduce sophisticated technologies or to change cooking habits. In Ethiopia, 90 percent of total energy is expected to be used in domestic cooking activities with no alternative substitute to fire wood [15]. Meanwhile, ICS are increasingly used in fuelwood-based countries [6,15,16], often supported by carbon funding [17,18]. Under the Clean Development Mechanism (CDM), there is an increasing number of projects and programs distributing ICS. Notably, ten programs of activity (PoAs) with an emphasis on Sub-Saharan Africa were successfully registered in 2013 [19]. Based on an evaluation of the UNFCCC registry [20], CDM cooking stove projects generally claim emissions reductions between one and five tons per ICS, depending on stove efficiencies, baseline fuel consumption and interpretations of the applicable CDM methodologies. There are however still few CDM credits issued for ICS projects, while more credits have been issued for ICS projects through the voluntary market [18], with approximately 5.8 Mt·$CO_2$ in 2012 [21].

In Ethiopia, ICS are disseminated by various initiatives (such as the Gaia project [22] and a CDM project implemented by World Vision [23]). Estimates from the Gesellschaft für Internationale

Zusammenarbeit (GIZ) state that 455,000 ICS were commercially distributed in Ethiopia until 2011 [24]. The preparation of Ethiopia's staple food, *injera* [25], requires a special baking plate, which necessitates a particular design for an ICS. To address this need, the so-called "*Mirt*" stove was developed in the 1980s and has been continuously improved since that time [20,21]. Dissemination projects in Ethiopia state that "*Mirt*" stoves have shown good acceptance for *injera* baking, with dissemination projects often being extended due to higher demand [21,22].

Together with worldwide initiatives to disseminate ICS, there is also increasing research to investigate if ICS can really cope with fuelwood scarcity and to estimate their effectiveness under daily life conditions and their acceptance [22,23,26–28]. While some studies report a significant fuel reduction [24,25], others have failed to prove any fuel reductions, but have shown other advantages related to the use of ICS [29–31].

The fuel saving impact of ICS is a complex issue. Most estimates of fuelwood savings, including those for the generation of carbon credits, are mainly based on fuelwood use in the baseline scenario, the rate of usage of the ICS and the efficiency of the ICS in comparison to a traditional stove [32]. For the comparison of stoves, laboratory assessed values are often used [13,33]. For a full picture of fuel savings, including all relevant factors, such as possible changes of cooking habits, empirical evidence on performance under field conditions is needed, directly comparing fuel consumption of users and non-users of ICS [26].

The overall objective of this empirical study is to assess the potential carbon impact of ICS in the UNESCO Kafa Biosphere Reserve. Specific research questions are:

- What quantity of fuelwood is consumed in households per day where ICS are used, in comparison to households where conventional stoves are used?
- What were the success factors for acceptance of ICS by the targeted households and what are the lessons learned for the implementation of fuel efficient stove projects?
- What is the expected impact of the distribution of ICS on carbon emissions at the household and regional level?

## 2. Study Area and Project Setup

### 2.1. Study Area

The study area is located in south-western Ethiopia, one of the last areas in the country with considerable forest cover. The Kafa province, within the Southern Nations, Nationalities and Peoples' Region (SNNPR), is characterized by a valuable expanse of Afromontane forest with a remarkable abundance of endemic coffee (*Coffea arabica*) [34,35]. The occurrence of wild forest coffee has economic significance to the local population, and internationally in the matter of coffee breeding [34].

Various initiatives have been undertaken to protect the unique forest resources in Kafa. Through the Man and Biosphere Programme (MaB) of UNESCO, the Kafa Biosphere Reserve (BR) was inaugurated in the region in June 2010. The BR covers 7500 km$^2$ with 47% forest cover [35]. The BR concept is based on 3 inter-related zones, each with different conservation functions (see Figure 1). First, a core zone is totally protected from all uses. The buffer zone is reserved for ecologically-sound land use concepts. Finally, the transition zone combines different interests towards the aim of using

resources sustainably [36]. The area is mountainous, with elevations ranging from 750 to 3360 m above sea level and has distinct climate seasonality. According to data between 2010 and 2014 (until March) from the weather station within the BR (Wushwush; 7°20′66.53″ N, 36°7′34.97″ E), two thirds of annual precipitation (total 1800 mm·yr$^{-1}$) occur between May and September, during which time the mean temperature was below the annual mean of 19.45 °C.

Since 2011, a joint initiative of NABU (Nature and Biodiversity Conservation Union) and local partners, including the Kafa Zone Department for Water, Mines and Energy in the regional state of SNNPR, has enabled access to ICS for rural communities in the Kafa region, with funding from the German Federal Ministry for the Environment. This measure is included in the Kafa Biosphere Reserve management plan, which is aimed at conserving local forests, improving the situation of rural communities by reducing fuelwood expenses and improving health conditions through less detrimental smoke production. The stove dissemination project is focusing on areas near the BR boundary, where rural communities have previously lacked access to ICS.

**Figure 1.** Geographic location of the UNESCO Biosphere Reserve and its zonation according to Man and Biosphere (MAB) criteria.
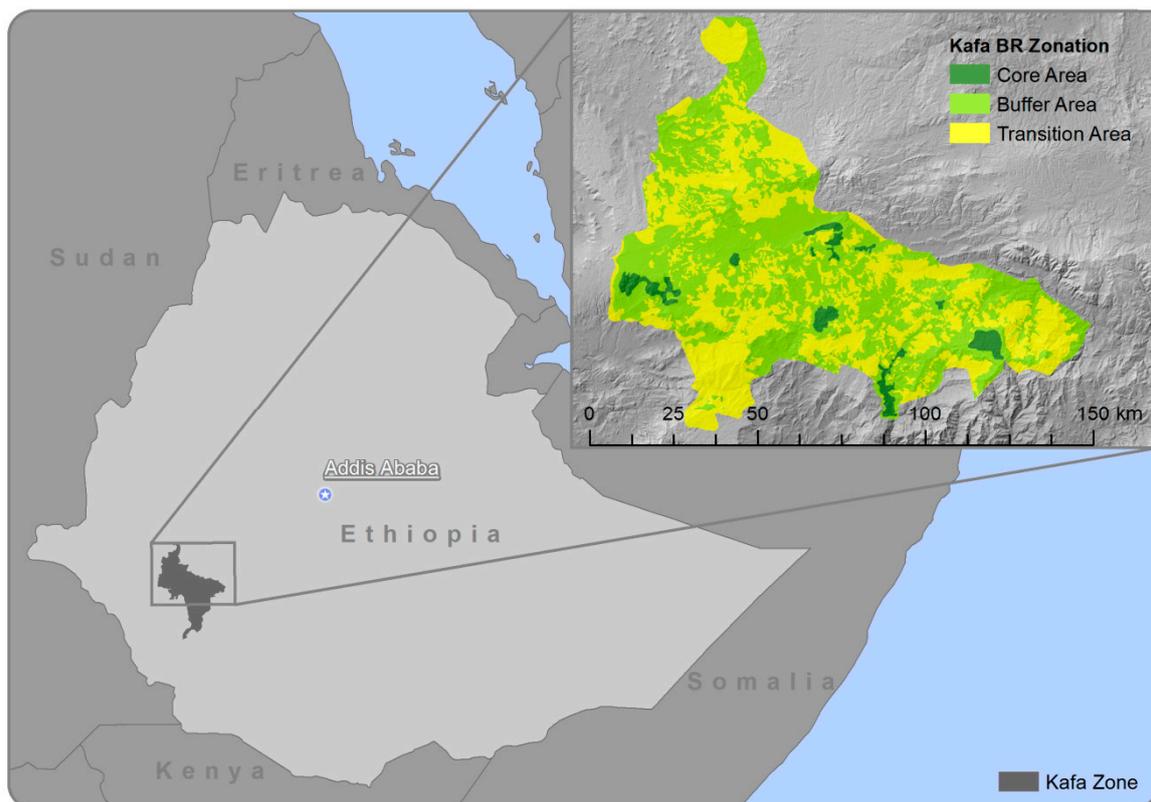


According to the census of 2002 (Central Statistical Authority 2004), the study area had a population of 620,247 with a relatively high population density of 130 (p/km$^2$) and an annual population growth of 2.95% (drawn from population growth from 1998 and 2002); the population is estimated to be 879,186 for 2014 (population density 185 (p/km$^2$)). *Woredas* (administrative units equivalent to municipalities) in the BR with high population generally show less forest cover.

A forest loss of 50% within the last 37 years has been reported for South-west Ethiopia [37]. Agriculture expansion is the main proximate driver of deforestation in the BR, while fuelwood

consumption is the main direct cause of forest degradation [35], which reflects the situation of the entire country [7]. In order to compensate for limited use of resources inside the strictly protected core zone, forest plantations have been established in the frame by the project since 2011, along with the promotion of community-based participatory forest management (PFM) [35,36]. Another activity to support the conservation and sustainable use of forest resources is the distribution of ICS. The initiative from NABU in the BR is one of the largest ICS dissemination projects country-wide, with 11,156 ICS distributed over 11 *Woredas* by 2013. The national and international importance of one of the last remaining natural forests in Ethiopia and the direct collaboration with governmental and non-governmental actors make the BR an ideal setting for this study.

*2.2. The Improved Cooking Stove (ICS)*

ICS have to be adapted to the cooking habits of the stove users. Many different models, mainly with a small heating plate radius on which to rest a pot, have been field-tested in different countries [6,15,35]. The ICS designed specifically for the purpose of cooking *injera*, the fermented flat bead staple food of Ethiopia and Eritrea, and is referred to as a "*Mirt*" stove. The *injera* is traditionally prepared on a clay plate, called a *mitad*, with a radius of about 60 cm and a thickness up to 4 cm. The thermal conductivity of the *mitad* is low, which supports the local baking method with virtually no fat used for *injera* baking. Traditionally, the *mitad* rests upon three stones surrounding an open fire. The *mitad* is locally produced and is sold separately from the ICS, which in practice often causes efficiency losses due to improper fitting.

The stove is produced by six main manufactures in the Kafa BR, and is made from cement and local materials, like river sand. Due to the weight and bulk of the stove components, transportation is an issue, so the production sites serve as distribution points. The end user assembles the six parts of the stove and closes the gaps with clay. The assembled stove is a closed body, were the *mitad* sits above a combustion chamber (Figure 2). Additionally, a prolonged chimney can simultaneously be used for heating food or beverages. Opposite the chimney, there is an inlet for biomass fuel and air.

**Figure 2.** "*Mirt*" stove, slim version.
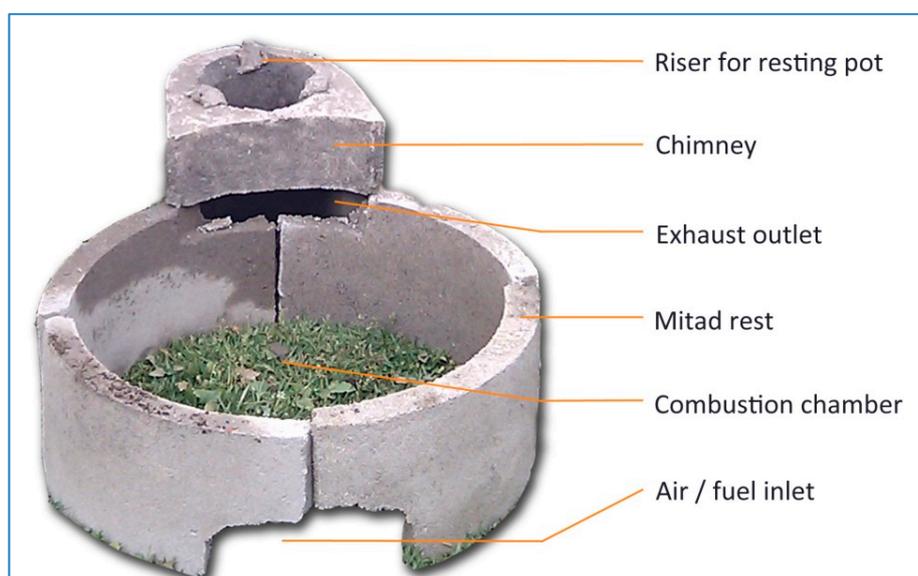
The stove comes in two versions, including the classic "*Mirt*" stove, which has thicker walls and the slim "*Mirt*" stove, which is lighter and more fragile. The classic stove has a lifespan of 5 years [18,38], while the slim version is conservatively estimated to last for 3 years.

Within the project, the stoves were offered free of charge, while the transportation was organized and paid by the end user (mean transportation costs 15 ETB; SD = 5.6; approximately $3 USD).

## 3. Methods and Materials

### 3.1. Household Survey

Interviews were conducted with users and non-users of the ICS. ICS users to be interviewed were sampled out of a list of households who had received an ICS under the NABU project. Only households that had been using the ICS for at least two months and lived close to the road network were considered. Since the field survey started in an early phase of the dissemination project, these criteria were fulfilled by 266 ICS stove users, all of whom were selected for an interview by forest rangers. Ninety six complete questionnaires were returned from interviews with ICS users, as well as 52 questionnaires from interviews with non-ICS users. The remaining interviews had mainly been conducted by persons who had not taken part in corresponding trainings, which had caused serious misunderstandings.

Within the NABU project, forest rangers and the local NABU staff selected the beneficiaries of ICS according to criteria that should guarantee access independent of income and educational level. The final selection mainly depended on the corresponding local staff, who also considered social criteria, such as woman household leaders. Additionally, a balanced spatial distribution of ICS had been pursued, including beneficiaries from both rural and urban areas and from many different *Kebeles* (administrative units comparable to villages or neighborhoods). Although the selection of beneficiary households was not done on a random basis, ICS users probably constitute a representative sample of all targeted households by the dissemination project in the BR. The minimum usage time of two months was considered sufficient to fully adopt the ICS, since, contrary to many other ICS [39], stove design and the means of operation of the disseminated "*Mirt*" stoves do not differ greatly from traditional fireplaces to bake *injera*.

Traditional stove users were selected randomly in the neighborhood of the selected ICS user households. Fifty two complete questionnaires were returned from these. This approach was chosen in order to make sure that non-ICS users live under the same conditions, so that they clearly represent the baseline scenario. Household size, *injera* cooking frequency and urban/rural distribution, which, according to other studies, might influence the stove efficiency [16], are statistically not different between non-ICS and ICS users, though the household size was slightly larger for non-ICS users, without being statistically significant (*p*-value of difference 0.246, Table 1). Despite the fact that no explicit matching approach had been chosen to select interviewees, as suggested by Mueller *et al* [40] for studies on health-effects of ICS, a significant bias is not plausible due to the high degree of similarity (Table 2) [41], and also because fuel consumption is probably less sensitive to living conditions than health. Fuel consumption of other biomass fuels besides fuelwood does not show significant differences between both groups. Only fuelwood as the most important fuel was analyzed

quantitatively. Charcoal is not used to prepare staple food; it is only used in small quantities for heating beverages in the study area.

**Table 1.** Characteristics of questionnaires' study households stratified by stove type.

| Characteristics of HH | Non-ICS User (n = 52) | ICS User (n = 96) | *p*-Value of Difference [1] |
|---|---|---|---|
| HH size (mean \| SD) | 5.38 \| 2.028 | 6.32 \| 2.112 | 0.246 |
| No. of *injera* session per week (mean \| SD) | 2.52 \| 1.23 | 2.72 \| 1.122 | 0.26 |
| Town \| rural [2] | 27 \| 20 | 53 \| 40 | 0.278 |

[1] According to chi-square or Fisher's exact test; [2] data points "Town" refer to the town center within a Euclidean distance of 1500 m.

**Table 2.** Biomass fuel use beside fuelwood stratified by stove type.

| Biofuel beside Fuelwood | All (n = 148) | Non-ICS User (n = 52) | ICS User (n = 96) | *p*-Value of Difference [1] |
|---|---|---|---|---|
| Charcoal (n (%)) | 80 (54) | 28 (53.7) | 52 (54.2) | 0.97 |
| Crop residues (n (%)) | 36 (24.2) | 14 (27) | 22 (23) | 0.588 |
| Bamboo (n (%)) | 10 (6.8) | 5 (9.5) | 5 (5.1) | 0.308 |

[1] According to chi-square.

The questionnaire was developed according to the factors that likely influence fuel consumption and subsequently tested in the field. Most questions were closed-ended [12,15,42]. Data collection was carried out by interviews conducted personally by the first author and by a team of forest rangers from the Kafa BR, which is distributed over all *Woredas*, guaranteeing a spatial balance of the sampling. Forest rangers conducted the interviews in the *Woreda* where they live to ensure maximal confidence between interviewees and interviewers. It was elucidated to interviewees that negative feedback would be as important as positive feedback, in order to improve ICS distribution. The questionnaire contained a large list of questions related to fuelwood use cooking habits and the socioeconomic situation of households. Parameters that were evaluated in this paper are listed in Table 3. The interviews were conducted from February to August 2012, which covers both the dry and the rainy season in the Kafa region.

**Table 3.** Relevant parameters assessed in the field survey.

| Parameter | Unit | Way of Measurement |
|---|---|---|
| Location by interview via GPS positioning | | GPS receiver |
| Type of fuelwood (tree species) | | Identified by interviewer |
| ICS user | Yes/no | Direct question |
| $HH_n$: household size | persons | Direct question |
| Type of fuelwood | tree species | Identified by interviewer |
| Other type of biomass fuel | kind | Direct question |
| $f_d$: daily fuel consumption without *injera* baking | kg wood | Piled by interviewee, weighed (digital scale, 0.01 kg accuracy) |
| $f_i$: Fuel consumption for one *injera* session | kg wood | Piled by interviewee, weighed (digital scale, 0.01 kg accuracy) |
| $t_w$: Frequency of *injera* preparation | Times per week | Direct question |

Since *injera* is not prepared daily, the household member responsible for cooking was asked to set aside a fuelwood pile that represented daily fuelwood without *injera* baking fuel and a second pile representing the fuelwood amount used for one *injera* session. Both wood piles were measured with a digital balance by the main author or the local ranger. Other biomass fuels, such as crop residues, bamboo or woody waste products, were addressed in the questionnaire, but were not quantified through weighting. This information was incorporated in the carbon calculation as renewable biomass.

To be able to distinguish the type of fuelwood, perform correct measurements and address the questionnaire in a correct way, the ranger team received a two-day training.

### 3.2. Stove Efficiency

In a small number of randomly selected households (n = 14), a performance test of the ICS and the traditional stove was conducted, in order to quantitatively determine the efficiency gain from using the ICS. A controlled cooking test (CCT) [43] was conducted on both stove types. To minimize the variation in influencing factors, the same fuelwood was used in all test procedures (*Olea africana*; 14%–18% wood moisture). The test followed the standard protocol of the Household Environment and Health (HEH) Project described by Bailis [44–46] with slight modifications. Each participating household was asked to prepare enough dough for a typical *injera* session. Fuelwood and the amount of dough were then weighed. The time from the start of ignition to removal of each *injera* was recorded. After finishing the food preparation, the remaining wood was weighed, as well as charcoal and ash produced through combustion. The specific fuel consumption (*SC*) was calculated using fuelwood type/moisture ($m$), the amount of dough consumed ($W_f$), the equivalent dry wood consumed ($f_d$) and expressed as grams of fuelwood used to bake 1 kg of dough.

$$SC = \frac{f_d}{W_f} \times 1000 \tag{1}$$

In total, there were 9 tests conducted for ICS and 5 tests for the three-stone method. In the context of the controlled cooking test, the effect of the number of *injeras* baked per session had on specific fuel consumption was also analyzed.

### 3.3. Spatial Factors that Influence Fuelwood Consumption and Reduction

Spatial parameters may also influence the fuelwood consumption, as found in several different studies [16,47,48]. All questionnaires were geocoded and related to existing geodata in a geographic information system (GIS) using a spatial join. The influence of forest cover on fuelwood consumption was analyzed by grouping households according to *Woredas* and then relating fuelwood consumption to the *Woredas'* specific forest cover data. Furthermore, we analysed whether the different Biosphere Reserve zones with their specific restrictions had an influence on the fuel consumption (distance of interviewed household to the nearest core zone). Additionally, a possible influence of other spatial factors was analyzed, such as distance to town, distance to road or the distance to the forest edge using ordinary least squares (OLS) linear regression.

*3.4. Side Effects Leading to Fuelwood Reduction*

While using an ICS, different side effects can positively contribute to save fuelwood. These side effects could only be partly integrated into the fuelwood saving calculations, but might offer more potential for in-depth analyses. The factors that were analyzed include the preparation of non-*injera* food on the chimney and the use of biomass derived from sources other than wood as fuel.

*3.5. Impacts on Carbon Balance*

The probable impact of fuel savings by using ICS on carbon stocks in the study area was evaluated by estimating total carbon savings achieved by all of the approximately 11,000 ICS disseminated, corrected by considering the sources of fuelwood and fuelwood species according to the results of the interviews. In this way, the fact that only a part of fuelwood stems from unsustainable sources was taken into account. The calculation was based on IPCC default net calorific values, emission factors and carbon storage in forests (Table 4, [49–51]), according to the formula:

$$E = fuelwoodsaved \times fNRB \times NCV \times EF \tag{2}$$

where:

E, emissions;
fNRB, fraction of non-renewable biomass;
NCV, net calorific value (for wet wood);
EF, default emission factor (per unit of energy).

**Table 4.** Parameters used for calculating carbon emissions.

| Parameter | Value | Source |
|---|---|---|
| Annual wood savings per stove | 1277 kg | Table 5 |
| Net calorific value fuelwood (wet basis) | 15 MJ/kg | [49] |
| Emission factor fuelwood | 112 g·$CO_2$/MJ | [50] |
| Conversion $CO_2$/C | 3667 | Ratio molecular weights |
| Fraction of non-renewable fuelwood | 50% | Estimated (Section 4.5) |
| Above ground carbon content per ha Kafa forest | 95 tons | [51] |

## 4. Results and Discussion

*4.1. Fuelwood Savings Due to ICS Introduction*

Results show significant fuelwood savings of nearly 40% for *injera* baking, with annual fuelwood savings per household of 1277 kg. We found that on average, *injera* is only baked 2.7 times per week (Table 5). According to other fuel saving studies [15,52–54], *injera* baking accounts for between 40% and 65% of the entire household cooking fuel consumption in Ethiopia. Our household survey for the Kafa region indicates a share of about 38%. The difference might be explained by greater consumption of non-*injera* bread in the Kafa region by the relatively high fuel consumption of non-*injera* cooking. The fact that households using "*Mirt*" stoves were on average slightly smaller than non-user households should not significantly influence the results. If there were a small effect, it should lead to an

underestimation of fuelwood savings, since there may be some economies-of-scale effects in larger households [55].

Interestingly, we also found that ICS users consume 9% less firewood for cooking purposes other than *injera* baking (see Table 5). This could be explained by the fact that while using the ICS, users also prepare sauces or beverages in pots that are placed on the chimney. Furthermore, the remaining thermal energy of the ICS after the *injera* preparation is often used to prepare a specific breakfast food consisting of dried *injera*.

Test results for the difference of used fuelwood for injera cooking between Non-ICS user (n = 52) and ICS user (n = 96) are significant according to the Mann-Whitney U test (95% CI; $p$ = 0.000). This confirms that ICS users consumed significantly less fuelwood per *injera* session and person. Table 5 summarizes the main results.

**Table 5.** Fuelwood savings due to the introduction of "*Mirt*" stoves on a yearly basis.

| | Non-ICS (kg fuelwood per capita and year) | ICS (kg fuelwood per capita and year) | Fuelwood Savings (relative) | Fuelwood Savings (absolute) |
|---|---|---|---|---|
| *Injera* cooking * | 399.8 (*SD 195.2*) | 244.5 (*SD 118.11*) | **38.9%** | **155.3 kg** |
| Non-*injera* cooking ** | 657.3 (*SD 314.7*) | 598.5 (*SD 314.0*) | **8.94%** | **58.8 kg** |
| Total cooking | 1057 | 843 | **20.2%** | **214.0 kg** |
| **Total annual fuelwood savings per ICS (**household size of 5.97, *SD 2.08***)** | | | | **1277 kg** |

\* On average, 2.7 *injera* baking sessions per week (*SD 1.11*); ** savings are probably due to sauce cooking on the chimney.

The results presented in Table 5 are based on household size and the number of *injera* sessions per week on average. Due to the questionnaire design, the fuelwood was weighed for a whole household, but for comparison reasons with other fuelwood estimations [6,39], the calculation was down-sampled per capita. The average household size was 5.97 (SD = 2.085) and was not significantly different between non-ICS and ICS-users. Regarding all cooking activities (like sauce preparation, heating beverages, baking local bread and *injera*), the use of an ICS caused a relative fuel savings of 20.25%.

In addition to the ICS, 30% of all ICS users were found to be using the three-stone fire occasionally for *injera* baking. In specific situations, like celebrations, some users fell back on the use of three stones for *injera* baking, possibly due to the longer ignition time of the ICS. The longer ignition time of the ICS "*Mirt*" has also been described in other studies [52,56] and has the potential to slightly reduce the positive effects of the ICS.

A comparison with the national woody biomass inventory from 2004 [15] shows comparable results to our study. While we found an annual firewood consumption of 1057 kg/person for non-ICS users, the biomass inventory reports 1152 kg/person for the high forest areas of the SNNPR region. Fuel consumption in the Kafa region is very high compared to other rural regions in Sub-Saharan Africa countries, such as Uganda and Kenya, where the mean annual consumption of fuelwood was estimated at 542.32 kg/person [12] and 600.9 kg/person [16], respectively. This is also confirmed by other studies [26] and can be explained with the inefficiencies in *injera* baking. Due to the specific cooking characteristics in this region, the transferability to other Sub-Saharan countries is limited. Comparably high values are reported from North East India, where an average fuelwood consumption of 1168 kg/person was found [57].

## 4.2. Efficiency Testing

The controlled cooking test nine ICS and five three-stone fires found total energy savings to be 24.3% (Table 6). These savings are clearly less than the result of a controlled cooking test conducted by Gulilat [52], where fuelwood savings of 48.8% were found. The difference between laboratory test results and those obtained in this study can be explained by the better field performance of the three-stone method. It was observed that experienced housewives operating three-stone stoves developed various strategies to save fuelwood, which were not observed while operating the ICS. Furthermore, the three-stone method is quite robust against different stove setups, while the ICS needs a specific setup to achieve the highest efficiency values. In this study, it was often observed that the cooking plate (*mitad*) does not perfectly fit to the standard combustion chamber diameter of the stove and caused undesired heat release.

The relatively high coefficient of variation results from the different influencing parameters (e.g., different amount of dough, different stove setup, skills of cooks) and a very small test sample, but it is comparable to other empirical ICS studies elsewhere [58]. Under laboratory test conditions, where all parameters are standardized, the CCT has a coefficient of variation (CV) between 5% and 10% [59].

**Table 6.** Results of efficiency testing according to controlled cooking test (CCT) per *injera* session.

| | Specific Fuel Consumption (g·wood/kg·dough) | |
|---|---|---|
| Test No. | Three stone fire CCTs | ICS CCTs |
| 1 | 673 | 414 |
| 2 | 454 | 495 |
| 3 | 495 | 353 |
| 4 | 384 | 336 |
| 5 | 593 | 477 |
| 6 | | 380 |
| 7 | | 489 |
| 8 | | 293 |
| 9 | | 301 |
| Mean | 519.8 (SD = 114.3; CV 22%) | 393.1 (SD = 79.4; CV 20.1%) |
| | Difference against baseline stove (absolute): 126.7 (g/kg) [1] | |
| | % difference against baseline stove (relative): 24.3 (%) | |

[1] According to the Wilcoxon–Mann–Whitney *U*-test (95% CI; $p = 0.042$), statistically significant.

The difference of CCT results to the aggregated saving rate of 39% found in interviews may be partly explained by the use of waste biomass of exclusive ICS users, as described in Section 4.4 of this study, which is indirectly included in the household data, but not considered within the CCT. Furthermore, the use of saved thermal energy after the actual cooking session (e.g., for preparing dried *injera* bread or *firfir*) may contribute to a better efficiency rate for the household survey. Under test conditions, even in their homes, users may have made a higher effort to bake efficiently, which may have led to relatively higher efficiency gains for traditional stoves. Accordingly, this result should be carefully applied in other study regions.

The discrepancy in the relative fuel savings found in this study and the laboratory study of Gulilat with a stated fuel reduction of 42% [52] is likely rooted in the study designs. The latter study calculates the reductions on self-conducted CCTs for ICS and is using one data point for the three-stone method (1031 g/kg), which is much higher than in his study. Accordingly, the baseline scenario of Gulilat is based on a much higher fuel consumption, thus causing better efficiency rates for ICS.

Worth to mention is a strong negative correlation ($R^2$ = 0.7514) between the duration of cooking sessions and specific fuel consumption was observed. This relationship was especially strong in households using ICS. While this finding is based on only nine data points (Table 6), it is plausible when viewed as a result of economies-of-scale and considering the storage of heat in the ICS once it is operating.

Figure 3 suggests that the number of *injera* baked per session on an ICS may be a good proxy for the specific fuel consumption, and the duration of *injera* sessions seems to have a decisive impact on fuel consumption.

**Figure 3.** Linear regression of specific fuel consumption (*SC*) on the number of baked *injera*s per session using ICS.
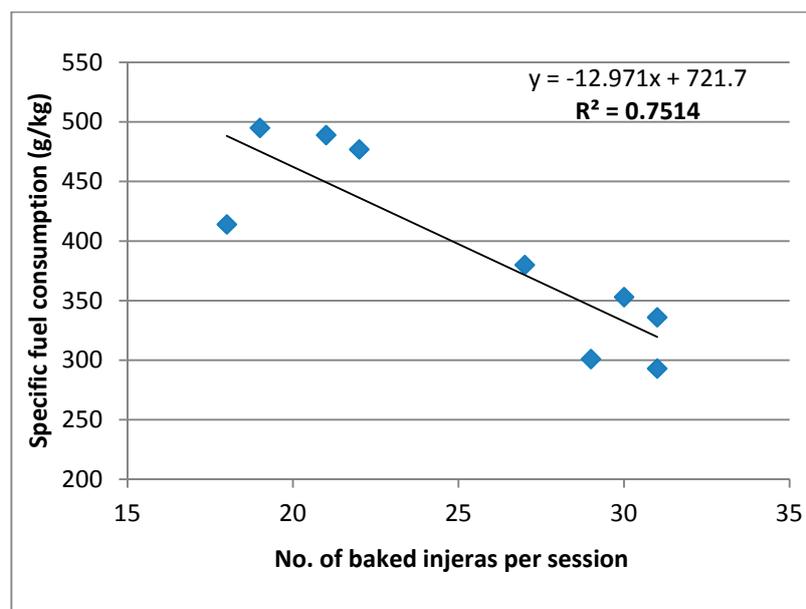


*4.3. Spatial Factors that Influence Fuelwood Consumption and Reduction*

According to satellite imagery analysis on forest cover, which shows that 47% of the BR is occupied by forests, the Kafa Biosphere Reserve still offers a considerable amount of fuel resources [35]. Forest cover differs significantly among *Woredas*. As shown in Figure 4, there is a weak positive correlation between forest cover and fuel consumption per person and *injera* session (Pearson's correlation coefficient = 0.503; $p$ = 0.069). The more forest cover a *Woreda* has, the higher the fuel consumption for baking *injera*. For example, Chena has a forest cover of 29% and an average fuel consumption of 1.83 kg/person, while Saylem with 58% forest cover has an average fuel consumption of 2.65 kg/person. This fact could be explained with alternative use of fuels (e.g., dung, crop residues) in regions with fuel

shortage. Conversely, when the fuel supply is high, there may be less incentive to use the resources conservatively [33].

The potential influence of BR zonation on fuelwood consumption was also tested. As most of the samples were taken in the transition zone, the distance to the nearest core zone was calculated. All questionnaires in a distance reasonable for fuel collection (<5 km) were considered in this analysis (n = 71). The proximity to core zones was slightly positively related to fuel consumption for ICS users ($R^2 = 0.12$), but had no effect on households using three-stone fires ($R^2 = 0.01$).

In general, this finding may indicate that restrictions on fuelwood collection in the core zone lead to reduced fuelwood consumption and use of alternatives. A possible bias here is the unequal distribution of core zones within the BR and the distance consideration as Euclidean distance. The analysis of other spatial factors, such as distance to the next town, distance to the next road or the distance to the next forest, edge did not show any significant correlations.

**Figure 4.** Fuel consumption kg/person according to forest cover (%).
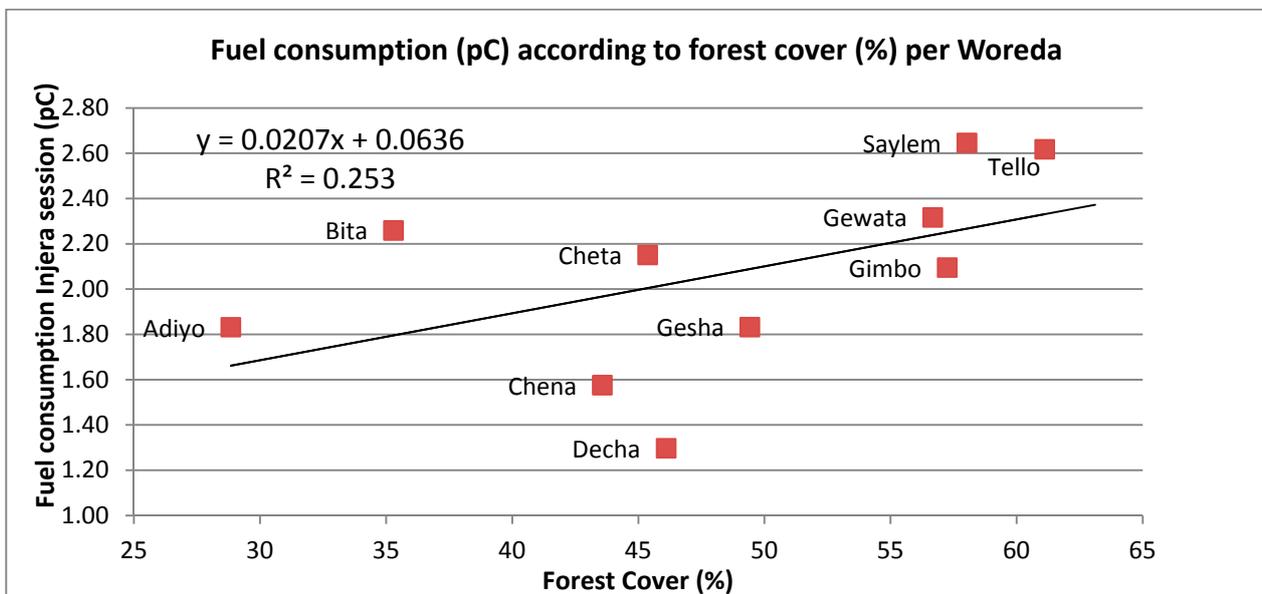


*4.4. Side Effects Leading to Fuelwood Reduction*

Ninety six percent of ICS included a chimney. While all users used the ICS for preparing *injera*, 53% of them additionally prepared *wot*, 27% prepared beverages and 15% used the remaining thermal energy for roasting coffee. Boiling water for purification is not practiced in the study region. Construction problems of the chimney were named as a constraint to extend the use of the chimney.

Besides expensive or unavailable alternative fuel sources, such as kerosene or electricity, some additional biomass fuel alternatives are commonly used in the study region. Most of them positively contribute to forest conservation, because they are based on waste products rather than forest biomass. Whereas crop residues were used by households independently of the presence or absence of ICS (31.3% of ICS user; 38.5% of non-ICS), only ICS users reported using wood chips, coffee pulp, leafs and small branches. ICS users explained that the stored thermal energy after *injera* baking is often used to produce *firfir*.

*4.5. Impacts on Carbon Balance*

The results of our empirical study show that each ICS in use leads to average fuelwood savings of 1277 kg per year (Table 5). Assuming a net calorific value of 15 MJ/kg [49] and an emission factor of 112 g of $CO_2$ per MJ of fuelwood [50], this corresponds to 2.145 tons of $CO_2$ per ICS per year. The final impact on carbon savings, however, depends on the extent to which fuelwood sources are renewable, *i.e.*, if there will be regrowth of the fuelwood extracted or not. This question is discussed in the following section, and the corresponding calculation is illustrated in Table 7, while Table 8 lists the estimated carbon savings in different dimensions.

**Table 7.** Estimated share of non-renewable biomass.

|  | **Stemming from Forests** | **Estimated Average Share of Non-Renewable Biomass** |
|---|---|---|
| Collected (60% of all fuelwood) | 60% | **50% (40%–70%)** |
| Bought (40% of all fuelwood) | 90% | |

**Table 8.** Estimated carbon savings.

| **Type of $CO_2$ Savings** | **Unit** |
|---|---|
| Annual $CO_2$ savings per stove assuming only non-renewable fuelwood | 2145 kg |
| Annual $CO_2$ savings per stove considering regrowth | 1073 kg |
| Annual $CO_2$ savings of all 11,000 ICS | 11,799 tons |
| Annual C savings of all 11,000 ICS | 3218 tons |
| Forest area corresponding to C savings | 34 ha |

According to the questionnaire, for 98% of all HHs (households) (n = 145), fuelwood is the most important fuel type, while charcoal (54%; n = 80), crop residues (24%; n = 36) and bamboo (7%; n = 10) are of secondary importance. Fuelwood from private plantations or woodlots with sufficient annual production can be regarded as renewable biomass and should be considered as a sustainable resource. Based on observations from forest rangers who performed the fuelwood measurements, it was found that 17% of fuelwood consists of eucalyptus from home gardens, community land, community plantations and governmental plantations. About 2% of fuels consisted of crop residues, lianas and dung. However, it was also found that 43% of fuelwood used stems from indigenous tree species (*Millettia ferruginea* 20.5%, endemic; *Olea africana* 14.6%; *Maesa lanceolata* 8%), which are mainly found in high and secondary forest. The remaining 38% consists of tree species that occur both inside and outside forests (e.g., *Allophylus abyssinicus*, *Prunus africana*, *Syzygium guineense*). Despite the first-hand observation of forest rangers, the interviewees commonly indicated that their fuelwood was derived mainly from home gardens, combined with other sources, like governmental forests and agroforestry systems (multiple answers were possible). The fact that governmental forests are only mentioned after home gardens may be due to a bias, since fuel collection from governmental forests is mostly illegal. Interestingly, 40% of fuelwood is purchased from the local market or from resellers for an average of 207 ETB per month (equivalent to approximately 10 USD), according to the interviews. This fuelwood is mainly sold by the partly nomadic minority group, the "Manjas", and it is known that it originates from natural forests [54].

Supposing that more than half of the fuelwood collected by households themselves also stems from forests, it is therefore justified to assume that 70% of total consumed fuelwood stems from forests. Most of this fuelwood stems from living biomass and should therefore be considered non-sustainable. While the exact fraction of non-renewable biomass used by households is difficult to know, we expect it to be in a range between 40% and 70% and use 50% as a conservative estimate for further calculations (Table 7). It is lower than the official estimate of 68.1% for the SNNPR region [54]. Our results indicate $CO_2$ savings of 1.07 tons per stove, translating to approximately 11,800 tons of $CO_2$ for all ICS distributed since the beginning of the NABU project (Table 5).

In terms of pure carbon, these savings correspond to approximately 3218 tons of C. Assuming a biomass carbon content of 50%, African moist deciduous forests, as in the Kafa region, are estimated to contain approximately 95 tons C per hectare [50]. Annual carbon savings from the 11,156 ICS distributed under the NABU project therefore correspond to the carbon content of approximately 34 ha of forest in Kafa. If we expect a four-year operation time of an ICS [53], this means that conservatively calculated (without taking the positive side effects into concern), 45,600 t of fuelwood are saved if regarding the whole dissemination project and assuming that 80% of the disseminated stoves are fully functional during their lifespan.

Since fuelwood collection represents a major driver of forest degradation, the major impact of fuelwood collection is expected to be on forest degradation rates rather than deforestation rates. For this reason, while the distribution of ICS is expected to have a positive impact over a much larger forest area, the actual effect on degradation rates is rather difficult to quantify. It is however worth mentioning that the dissemination of efficient stoves, like the ICS, directly tackles the most important driver of forest degradation in the study area and therefore constitutes a possible strategy to mitigate forest degradation.

## 5. Conclusions

The use of ICS under field conditions was found to lead to fuelwood savings of 38.9% for *injera* baking in the Kafa region. This seems to be a more realistic figure than the savings often claimed in ICS distribution projects, since efficiency values are usually based on laboratory experiments rather than field-based household studies, possibly leading to overestimates of fuelwood savings [33].

Positive side effects can still increase the total impact of ICS on the carbon balance, such as the use of wood chips, and additional fuel savings for cooking activities using residual heat from the stove chimney. The benefits of the ICS were found to be two-fold. On the household level, users reported less smoke, minimized risk of burning, better taste of the food and reduced expenditures for fuelwood. On the regional level, the dissemination of 11,000 ICS mitigates forest degradation and represents a saving of approximately 11,800 tons of $CO_2$ per year. ICS are an effective and efficient contribution to securing carbon storage in forests.

We found a significant correlation between the numbers of *injera*s baked per session and stove efficiency for the "*Mirt*" stove. This result should be confirmed by further research. The promotion of longer *injera* baking sessions may lead to additional fuelwood savings, by promoting strategies like community kitchens, for example. This concept may be particularly interesting if household size and baking sessions decrease in future due to urbanization and family planning [60].

Generally, "*Mirt*" stoves are designed primarily for *injera* baking, though additional cooking activities were observed in this study. To enhance the positive impact of these stoves, it is recommended to disseminate additional ICS for other cooking activities. Among others, GIZ Ethiopia is promoting the so-called *Tikikil* stove, a rocket-stove model. Data are still not sufficient to ascertain user satisfaction, but positive experiences are reported by GIZ ET [61], while Accenture Development Partnerships, 2012 [62], report still lacking acceptance. The *Tikikil* stove is already part of a CDM PoA dissemination project in Ethiopia [63].

Some improvements of the disseminated "*Mirt*" stove could positively contribute to fuelwood savings. The users often mentioned that the design of "*Mirt*" stoves is not appropriate for the separately bought clay *Mitad*. As these clay plates are produced traditionally by hand with unstandardized designs and sold at local markets, the perimeter can vary, leading to gaps between the stove and the clay plate that lessen the efficiency of the stove. Moreover, it seems that using clay plates, thermal energy is used very inefficiently. While alternatives made of metal are under development, it is still difficult to convince traditional households to adapt to these new designs, while their potential is clear by the fact that electric *Mitad*s only use metal plates [64].

For a better adaptation of ICS to users' demands, it seems to be important to better understand the strategies that households employ to respond to fuel scarcity. The study area has a forest cover of 47%, which implies the chance to make an important contribution for saving the remaining forests. On the other hand, the demand of users for ICS may be even higher in regions with less forest cover [65]. A similar dissemination stove project is in preparation by NABU in the Amhara region, which has only 3% forest cover. In this case, it would be interesting to compare the users' behavior with those of the Kafa region. This comparison could give valuable information on how the stove is adapted by users in a wider range of environmental conditions.

Finally, it can be concluded that the NABU stove dissemination activity was found to have a positive impact on fuelwood savings and carbon emission reductions, accompanied by a very high stove user acceptance. One reason for this might be the fact that stove users do not have to change their cooking habits, with the exception of a longer ignition phase.

Whereas some other sophisticated technologies might fail when there is no expert knowledge available (solar panels, for example), disseminated ICS can be simply repaired by users with local materials. Initial costs to run the dissemination are much lower than with sophisticated technologies, and the program can usually be started with relatively low logistic effort. Our study confirms that efficient cooking stoves, if they are well adapted to the local cooking habits, constitute a cost-effective and practical solution for simultaneously mitigating climate change, conserving forests and improving human livelihoods.

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## Author Contributions

Elisabeth Dresen designed and conducted the field study, analyzed the data and led the preparation of the manuscript, with support of Robert Müller in all phases of the study. Ben DeVries, Martin Herold and Louis Verchot revised conceptual and statistical aspects and helped editing the paper.

## Conflicts of Interest

The authors declare no conflict of interest.

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