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A cost-benefit analysis of livelihood, environmental and health benefits of a large scale water filter and cookstove distribution in Rwanda

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ABSTRACT

Public health interventions targeting contaminated drinking water and indoor air pollution may help to reduce two of the leading causes of death among children under 5 in Rwanda - diarrhea and pneumonia. These interventions also have the potential to provide economic benefits, including reduction in expenditures on fuelwood and time spent on fuelwood collection, environmental benefits through reductions in deforestation and greenhouse gas emissions, and additional economic benefits attributable to health impacts. We evaluate one such large scale intervention, the *Tubeho Neza* program in Western Rwanda using a cost-benefit analysis. This paper estimates monetized program benefits related to fuelwood savings, time savings, environmental and health benefits, which are then compared to the overall program cost, over a 5 year project year period. The total program cost is estimated at over $11.91 million, and total benefits at the means valued at over $66.67 million, for an estimated mean cost-benefit ratio of over 5.6. A sensitivity analysis of the major factors indicated a cost-benefit ratio range of approximately 1–16. The primary benefit identified is the environmental impact of woodfuel savings attributable to the improved cookstoves. This study estimates 118,000 tonnes of annual woodfuel savings in the Western Province may be attributable to the program in year 1, decreasing to 65,000 tonnes in year 5. These estimates suggest that this program may help to compensate for the government of Rwanda's projected regional woodfuel deficit of 106,000 tonnes per year by 2020. Overall, this study suggests that the *Tubeho Neza* program provides benefits in excess of the program costs.

1. Introduction

Public health interventions designed to address contaminated drinking water and indoor air pollution hazards in developing countries may under some circumstances deliver additional benefits. Importantly, the economic and environmental benefits can also contribute to the overall suitability and sustainability of an intervention. For example, advocacy of household water treatment methods replacing boiling can both reduce fuelwood consumption and provide time savings (Clasen et al., 2008; Peletz et al., 2012). Similarly, implementation of improved cooking stoves has the potential to reduce expenditures on purchasing fuelwood, and time from the collection of fuelwood. Additionally, reduction in fuelwood consumption can result in significant environmental benefits both locally through reduced deforestation and globally through reduced greenhouse gas emissions (Hutton et al., 2007a; García-Frapolli et al., 2010; Habermehl, 2007, 2008). Furthermore, the health improvements realized may translate into economic benefits to countries and communities.

In the Republic of Rwanda, where two of the largest contributors to mortality among children under five are pneumonia (18%) and diarrhea (8%) (United Nations International Children's Emergency Fund, 2012), interventions that can improve access to clean drinking water and reduce exposure to harmful indoor air pollution have the potential to provide significant health benefits. Additionally, Rwanda's 10.5 million people may benefit from the livelihood and environmental benefits from these programs. With over 80% of Rwandans relying on firewood as their primary fuel and over 40% boiling their water for treatment prior to drinking (National Institute of Statistics of Rwanda, 2012), decreased firewood demand from water filters and high efficiency cookstoves could help reduce the shortage in availability of firewood. Additional

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cost and time savings from reduced fuelwood consumption could help curb some of the economic burden on the approximately 80% of Rwandans who live on less than $2 per day (World Bank, 2011).

A cost-benefit analysis can provide insight into the relative contribution of these livelihood, environmental and health benefits. Public health programs advocating water treatment methods and improved cookstoves can vary greatly in quality, scale and impact, from small community driven projects to large scale government programs, from non-profit to for-profit models, and from subsidized to market based funding mechanisms. Because of the high degree of variability of impacts between these program models, understanding a particular program's ability to deliver benefits to the target population in a cost effective and sustainable way is essential to inform future interventions. This paper analyzes one such program, the DelAgua Health and Ministry of Health *Tubeho Neza* program in rural Rwanda, through the comparison of the program costs, and the potential benefits of the program related to fuelwood savings, time savings, environmental and health impact.

1.1. *Program setting and population*

The *Tubeho Neza* ("Live Well") program is a partnership between the Rwanda Ministry of Health (MOH) and the social enterprise, DelAgua Health (DelAgua), designed to deliver environmental health technologies to some of these poorest of Rwanda's households. An initial pilot phase of the program (Phase 1) was implemented in October of 2013 among approximately 2000 households (Barstow et al., 2014). Following the completion of several studies in Phase 1, including a health impact randomized controlled trial (Rosa et al., 2014), a large-scale (Phase 2) program among approximately 102,000 households was implemented between September and December of 2014 in Rwanda's Western Province. The program included the distribution of the EcoZoom Dura improved wood burning cookstove and the Vestergaard Frandsen LifeStraw Family 2.0 household gravity-fed water filter. In 2015, a further 250,000 cookstoves were distributed primarily in the Eastern Province (Phase 2). The intervention includes household level education and behavior change messaging to each household through MOH Community Health Workers. Currently, the program includes educational promotion activities as well as repair and replacement services throughout program households (Barstow et al., 2016). This paper considers only the costs and benefits attributable to the Phase 2 program.

Baseline woodfuel and water collections practices are shown in Fig. 1 and the cookstove and water filter interventions are shown in Fig. 2.

2. Materials and methods

The analysis here examines the costs and benefits of the *Tubeho Neza* program over a projected period of 5 years and is informed by field survey data, kitchen performance tests and controlled cooking tests, as well as two years of experience with the program implemented at-scale. Similar studies have been conducted on cookstove programs (Hutton et al., 2007a; García-Frapolli et al., 2010; Habermehl, 2007, 2008) and drinking water interventions (Hutton et al., 2007b) separately, but the authors are not aware of any cost-benefit analysis of a combined program. The cost-benefit model was designed based on the methodology outlined in the aforementioned referenced studies, with additional guidance from World Health Organization documents for conducting cost-benefit analyzes of household energy, and water and sanitation interventions (World Health Organization, 2004, 2006). Potential benefits include those related to livelihood and environmental impacts associated with the water filter and improved cookstove technologies implemented within the *Tubeho Neza* program. Further, health impacts were estimated based on experimental trials conducted within the program, and projected using emergent models. In this analysis, we consider only the operational phase of the water filters and stoves. We do not consider the full lifecycle costs or environmental impacts of the product production, transportation, or disposal.

2.1. *Cost estimation*

The cost of the program was quantified through an incremental cost analysis where intervention costs are separated into capital costs and recurrent costs. Investment costs describe all intervention costs incurred at the beginning of the intervention, including the cost of the hardware and the administrative and implementation costs. Recurrent costs are those which occur periodically throughout the lifetime of the program, including product maintenance and educational outreach activities. Given both technologies have an estimated lifetime of five years and replacements are not currently planned by the government of Rwanda or the implementer, this study considered only the capital and operating costs for an initial distribution, supported for 5 years.

To account for the differential timing of costs, a commonly used discount rate of 3% is applied to all costs and benefits occurring after 2014. As an important robustness check, we also examine results at 0% and 5% discount rates. We find that our overall conclusions are not sensitive over the range of discount rates. The net present value (NPV) can then be calculated using the following formula:

$$NPV_{costs} = \sum_{t}^{T} \frac{costs}{(1+r)^{t}}$$

where $\sum(t, T)$ is the sum of all costs at time periods from $t = 0$ to the end of the intervention $T = 10$ years, and r is the discount rate.

2.2. *Technology adoption quantification*

A data set collected by the implementer to meet the United Nations Clean Development Mechanism requirements for carbon credit issuance, a primary form of revenue to support the program, was used to quantify initial uptake and adoption values for cookstoves and water filters. In a recent study, the determinants of water filter and cookstove adoption in

Fig. 1. Woodfuel and water collection practices in Rwanda.

Fig. 2. The cookstove and water filter interventions.

this intervention were examined, including spatial, temporal and demographic characteristics (Fankhauser et al., 2019). This examination indicated that rural households adopted these products at a higher rate than more urban households, and that household adoption was highly correlated to mean community adoption.

2.3. Kitchen performance test

The kitchen performance test (KPT) is comprised of two components; the measurement of household fuel consumption over multiple days and a quantitative survey to characterize fuel consumption and cooking practices. The KPT is performed within households where they are asked to prepare and cook meals as they normally would. Enumerators visited a household for four consecutive days, measuring the amount of fuel consumed for three 24-h periods with weight scales. Daily consumption over the four days is averaged and fuel consumption per person is calculated using a standard adult equivalence factor to obtain a normalized household size (Bailis and Edwards, 2007). The quantitative survey developed for this study included approximately 75 questions and takes about 45 min to administer. Questions primarily relate to a household's cooking and fuel procurement methods as well as socio-economic indicators. The survey was piloted extensively including a two day classroom training with enumerators and field based practice surveys in households.

A cross-sectional study was chosen as a randomized control trial (RCT) was being conducted for a parallel study and thus a control group of approximately 40,000 households had been previously identified (Nagel et al., 2016). Intervention households were chosen from the implementer's distribution list of approximately 102,000 households while control households were chosen from the list of control households which will eventually be used for distribution of products upon completion of the RCT. A two-stage, cluster sample design was used whereby 32 villages were randomly selected from both groups using a sampling frame proportionate to population size, and then three households were randomly selected within each village using simple random sampling, resulting in a sample of 96 households in both the intervention and control groups. Households that could not be found, did not consent or did not have an adult over the age of 18 responding were not surveyed and the next household in the randomly generated list was visited.

Descriptions of particular metrics derived from the KPT study are outlined in relevant sections below. Primarily, the fuel consumption results are used throughout the study where average per capita fuel savings were calculated as the difference between the control and intervention fuel consumption.

2.4. Controlled cooking test

To quantify fuel savings from the water filter, a controlled cooking test (CCT) was conducted (Household Energy and Health Programme, 2004). The CCT is a field based test where a household is asked to perform a specific cooking task as they would under normal conditions. Fuel used during that specific task can then be measured. In this case, three households in the KPT control area who normally boil their water for drinking were asked to boil water three times as they typically would and the amount of fuelwood used was measured. The volume of water was measured and households were asked questions related to their water treatment practices.

2.5. Impact estimation

Four impacts were analyzed for both the improved cookstove and water filter: fuel savings, time savings environmental benefits, and health benefits.

2.5.1. Fuel savings

To quantify fuel savings from the improved cookstove over a ten-year period, the savings in per capita fuelwood usage measured in the KPT study was multiplied by the total population of the intervention. The total fuelwood savings was then only applied to the population reporting the stove as their primary cookstove (90% in this model), with the cookstove adoption decreasing yearly by 10% until year five. The average price of fuelwood reported during the KPT survey ($2.08) was then used to monetize the fuelwood savings, with the minimum and maximum fuelwood prices additionally examined to assess any uncertainties in this value.

Any fuel savings attributable to the filter is assumed to be realized only among households who previously boiled their drinking water. A total of 26.6% of intervention households reported treating their water by some method before receiving the water filter, with 80.7% of these households reporting boiling their water. This suggests that 21.4% of households in the intervention reduce their actual fuel usage due to switching from boiling water to the water filter. The authors acknowledge that the behaviors underpinning this estimate (e.g. degree of post-intervention leakage) have not been rigorously evaluated, and some experts indicate that actual fuel savings from water filter interventions may be de-minimus (Hodge and Clasen, 2014). The controlled cooking test results were used to quantify total fuel savings per person each year, and with the above qualifications, total fuel savings are calculated based on the population that received the intervention, the percentage of the population who boiled water before receiving the filter, the percentage of the population who adopted the filter, with a 10% reduction in filter usage each year up to year five, and the fuel usage for a boiling event from the CCT. Similar to fuel savings from the improved cookstove, the total fuel savings from use of the filter is monetized using the average price of fuelwood.

2.5.2. Time savings

Time savings from the improved cookstoves were estimated from household's reported reduced time collecting firewood attributable to fuel savings.

2.5.3. *Environmental benefits*

The environmental benefit of the cookstove was assessed based on two metrics: locally from reduced deforestation and globally, attributable to reductions in carbon emissions. Deforestation has been quantified in the literature by estimating the cost of replacing any forest cover that would be lost were the intervention not in place, but we recognize that the biomass replacement cost likely represents the minimum value of this environmental benefit (García-Frapolli et al., 2010; Habermehl, 2007, 2008; Freeman et al., 2014). Both the cost of the tree saplings and the labor to plant them was calculated for this study. The total mass of fuel saved was converted to area of forest cover using the average biomass density in Africa (109 tons/ha) (Food and Agricultural Organization of the United Nations, 1997) whereby the labor necessary to plant 1 ha was measured in surveys and informal interviews. Additionally number of tree saplings was estimated based on area of forest cover by the tree density of Eucalyptus in Rwanda (1350 trees/ha) (Ministry of Natural Resources Rwanda, 2014) and monetized based on locally reported costs of Eucalyptus tree saplings ($0.26). A common wastage factor of 30% was applied to account for wood species that would be unusable as fuel (García-Frapolli et al., 2010; Habermehl, 2007).

Carbon emissions were estimated using the Clean Development Mechanism (CDM) for Small Scale Projects methodology (Clean Development Mechanism, 2015). Emission reductions are calculated using the following formula:

$$ER_y = B_y * f_{NRB,\,y} * NCV_y * EF_{biomass}$$

Where ER_y is the emission reductions during a specified year y measured in tons of CO_2 emissions (tCO_2e), B_y is the quantity of woody biomass that is substituted or displaced in year y, $f_{NRB,\,y}$ is the fraction of non-renewable biomass used in the absence of the project activity in year y (0.98 default CDM value for Rwanda), NCV_y is the net caloric value of the non-woody biomass that is substituted (0.015 TJ/tonne recommended default value for wood fuel) and $EF_{biomass}$ is the emission factor for biomass fuels (methodology specifies using 81.6 tons CO_2 per TJ of wood) (Clean Development Mechanism, 2015).

2.5.4. *Health benefits*

Health benefits from improved cookstoves are estimated using the Global Alliance for Clean Cookstoves hosted Household Air Pollution Intervention Tool (HAPIT). HAPIT, available online at (HAPIT version 3.1.1 https://hapit.shinyapps.io/HAPIT run on December 21, 2018), estimates Averted Disability Adjusted Life-Years (ADALYs) for adults and children combined based on pre- and post-intervention 2.5 micron sized particulate matter (PM 2.5) exposure, adoption rates, and scale (Pillarisetti et al., 2016). PM 2.5 in the main cooking areas was measured during the Phase 1 program in control and intervention areas. These PM 2.5 mean exposures are applied in HAPIT with mean control exposures in the main cooking area of $0.905\,mg/m^3$ used as the pre-intervention exposure and $0.485\,mg/m^3$ as the intervention exposure in the main cooking area (Rosa et al., 2014). Similar to the fuel savings estimates, an upper bound adoption rate of 90% was used in year 1, decreasing 10% a year to a lower bound of 50%. This is a conservative application of HAPIT as the model assumes a 100% adoption in the post-intervention PM 2.5 estimate, whereas the PM 2.5 data used in this study is the aggregate exposure inclusive of an adoption rate less than 100%. Therefore, to some extent ADALY estimates are doubly discounted by adoption estimates.

A more recent impact evaluation of this program at scale measured reported childhood diarrhea and acute respiratory disease (ARI), as well as personal particulate exposure and indicated significant health benefits, demonstrating a reduction reported child reported child diarrhea by 29% and ARI by 25%. However, this same study found no significant impact on 48-h personal exposure to log-transformed fine particulate matter (PM2.5) concentrations among cooks or children (Kirby et al., 2019a). The apparent discrepancy between these findings are hypothesized to be attributable potentially to the synergistic health benefits effects of reduced diarrhea and/or the benefits of cooking outdoors. Given that this health impact study identified a respiratory related health benefit of this program, in this cost-benefit analysis we chose to rely on the cooking-area exposure measures in order to quantify and value the health benefits potentially connected to the cookstove intervention.

Several approaches have been recently reviewed for measuring and calculating ADALY estimates associated with water and sanitation interventions (Anderson et al., 2018). Here, we use the Global Burden of Disease (GBD), published by the Institute for Health Metrics at the University of Washington (http://www.healthdata.org/) which provides DALY estimates for diarrheal disease. Using this data source, and accessing diarrhea disease ADALY rate for Rwanda, the GBD estimates a conservative lower bound of 1762 DALYs per 100,000 children under 5 attributable to diarrheal disease in Rwanda annually, and a lower bound of 2476 DALYs for all adults ages 5-50 (Evaluation, I. for H. M. and GBD Compare | IHME Viz Hub, 2016). DALYs for adults over 50 attributable to diarrheal disease increase dramatically; we therefore apply a conservative estimate of DALYs associated with ages 5–50 to all persons over 5.

2.6. *Ethics and consent*

The Rwanda National Ethics Committee (IRB #206/RNEC/2015) approved the protocol including all questions and the consent procedure. Additional approval was received from the University of Colorado Institutional Review Board (Protocol #: 15–0613). Each household enrolled provided informed, verbal consent after receiving details regarding the purpose of the survey. All respondents were over the age of 18. Consent was administered through a smartphone based survey with all records stored on a password protected server. Participants were given the opportunity to ask questions before consenting to participate. Additionally all households, regardless of consenting to the surveys were able to retain the filter and cookstove.

3. Results

3.1. *Program cost*

The capital costs reported were $30 per stove and $30 per filter, while the recurrent costs were $5 per stove and $5 per filter (Thomas, 2016). In this study, we conservatively increased these estimates to $35 per stove, and $40 per water filter, with recurring annual costs of $7 per device, per household. These higher estimates are used to include full overhead costs of the implementer.

The total cost of the program over a 5 year period with a 3% discount rate is estimated to be around $11.63 million, with an estimated cost per household of approximately $114. About 60% of costs are incurred during the initial implementation in year one, largely consisting of the initial costs of the stoves and filters.

3.2. *Technology adoption quantification*

The first verification, conducted in 2015 approximately six weeks to six months after distribution of the products reported the EcoZoom stove as the primary cookstove among 92.8% of households, while the LifeStraw water filter was reported as the water treatment method among 95.4% of households. The second verification survey, conducted approximately ten months to one year after distribution reported a 3.5% decrease in households reporting the EcoZoom as their primary cookstove and a 4.0% decrease in households reporting the LifeStraw as their water treatment method (Barstow et al., 2014). A recent survey conducted by the implementer 3 years after initial distribution reported 86.45% of stoves were operational (a 4.5% annual decrease) and 72.90% of filters (a 9% annual decrease).

To further assess uncertainty in the adoption rates, a range of filter and stove adoption values were modeled. An electronic sensor based monitoring activity was conducted in a parallel study wherein a sample of filters and stoves were instrumented with sensors measuring actual usage of the technologies. Sensor based measurements may provide more objective values because they do not rely on survey based data which can be biased (Wood et al., 2008; Andres et al., 2018). The study reported a stove adoption rate of 73.2% and filter adoption rate of 90.2% (Thomas et al.).

Therefore, a conservative decrease in adoption and/or functionality of the stoves and filters is assumed at 10% per year, for 5 years, at an initial adoption of 90% and a final adoption of 50%. These estimates are below the observed adoption rates reported by the implementer as well as independent evaluators.

3.3. Kitchen performance test

The KPT measured control household fuel consumption as 807.4 (St. Dev. 475.6) kg/person/year while intervention households consumed 548.3 (St. Dev. 355.9) kg/person/year, a 32% savings. Thus, fuelwood savings are found to be 259.1 kg/person/year, which is a value similar to other Sub-Saharan Africa studies (Gebreegziabher et al., 2018), and are used throughout the calculations. An important note is that the KPT fuel savings estimates are inclusive of “stove stacking” behavior wherein some households continue to periodically use their baseline stoves for some cooking events. Therefore, the KPT wood fuel savings estimate does not assume a total switch to the intervention stove.

3.4. Controlled cooking test

Households that reported boiling water as a treatment method, reported boiling an average of 2.17 L per person per week for drinking water. Households typically boiled in 5 L batches, which consumed an average of 3.03 kg of wood per boiling event. An average fuel consumption could then be calculated as 72.5 kg/person/year. The average time to boil the 5 L batch was 18 min, resulting in an average yearly time consumption from boiling of 402 min/person.

3.5. Time savings

Survey results indicated that of the households which primarily collect fuelwood (74.3%), 93.1% reported a decrease in time collecting wood, with 74.1% of reported activities with the extra time related to agriculture or other income related activities. Thus time savings are assumed to only be reductions in time to collect fuelwood (e.g. no change in cooking time) and it is assumed that liberated labor is used for economically productive activities.

To estimate the actual time saved, the reported time to collect one bundle of fuelwood was converted into a total time savings based on fuelwood saved between control and intervention groups, among the fraction of households which collect fuelwood (73%). Similar to the fuel savings calculations, as adoption of the cookstove is assumed to decrease by 10% per year up to year five, we also assume that total fuelwood collection time savings declines by 10% per year. Monetization of the time savings is estimated by applying the average hourly wage rate ($0.12) reported in the KPT survey to the reported time savings (approximately 2 h per bundle of wood). Additional analysis was conducted to evaluate the effect of this choice of the average hourly wage rate by also evaluating the results at the minimum and maximum reported wage rates.

3.6. Environmental benefits

The quantity of woody biomass used by the cookstoves following the carbon credit methodology cited earlier (B_y) is calculated using the following formula:

$$B_y = B_{baseline} * LF * \left(1 - \frac{n_{traditional}}{n_{improvedstove}}\right) * BU_{baseline} * UF*AF_{improvedstove}$$

Where $B_{baseline}$ is the average fuel used per person before the intervention (327.54 kg/person/year) (Government of Rwanda, 2009), LF is the leakage fraction to account for non-renewable biomass saved by the intervention (0.95) (Clean Development Mechanism, 2015), $n_{baseline}$ is the efficiency of a traditional stove (10%), $n_{improvedstove}$ is the efficiency of the improved stove (38%) (Aprovecho Research Center, 2012), $BU_{baseline}$ is the fraction of the intervention population which used biomass as their fuel source before the intervention (99%), UF is the fraction of total cooking performed on the improved stove (0.85) by accounting for stove “stacking” behavior where the household continues to use the traditional stove alongside the improve stove, and $AF_{improvedstove}$ is the fraction of the population that has adopted the improved stove. Additionally, because the intervention includes the water filter, the baseline fuel used ($B_{baseline}$) was reduced from 377.54 kg/person/year to 327.54 kg/person/year to account for carbon credits claimed from the reductions in boiling water for drinking (UNFCCC, 2013). Total emission reductions was then monetized based on a historical price of certified emission reductions for the African region, in October of 2015 when the first carbon credits for the program were issued ($5.40 per ton CO_2) (Carbon Pulse, 2015). As the price of carbon can vary significantly based on a number of factors the model was assessed at a low carbon credit price of $1 to a high carbon credit price of $30. These values capture typical current carbon credit prices during the project period (World Bank, 2014). We note that these are financial prices that reflect important distortions in the market for carbon credits, which likely understates their true value. The estimated social cost of carbon – the marginal value of the damages avoided by reducing CO_2 emissions by one ton - is approximately $40.00 (Interagency Working Group on Social Cost of Carbon, 2010).

With respect to the water filters, baseline emissions and leakage emissions were calculated using the following formulas:

$$BE_y = QPW_y * m * X_{boil} * SEC * \sum_i \left(BLfuel, i * f_{NRB} * EF_{projectedfossilfuel,i} * 10^{-9}\right.$$

$$LE_y = LF*BE_y$$

Where QPW_y is the total quantity of purified water per filter per year (2609.8 L), m is the fraction of households which are not already served by a safe drinking water source (0.99), X_{boil} is the fraction of the population which would have boiled water for drinking before the intervention (default to 1), SEC is the specific energy consumption to boil 1 L of water (3574.8 kJ/L °C based on the baseline stove efficiency of 10%), and $BLfuel, i$ is the proportion of the baseline which uses firewood (0.99).

3.7. Health benefits

Health benefits from the water filter intervention are estimated using the results of the health impact evaluation conducted during the Phase 2 program. Between the control and intervention areas, the prevalence of reported diarrhea among children under 5 was reduced by a gender and age corrected 29% from a prevalence of 15.3% in the control area to 13.7% in the intervention area (Kirby et al., 2019a).

Estimated ADALYs associated with the cookstove intervention as estimated by HAPIT total 13,919 across a five-year stove product lifetime or about 556 ADALYs per 100,000 people per year. Estimated ADALYs associated with the water filter intervention total 5,477, or approximately 239 ADALYs per 100,000 people per year. This estimate is consistent with the range offered in a recent probabilistic model estimating a mean of 520 (SD 326) ADALYs per 100,000 persons associated with high adherence to a water treatment technology with a moderate risk exposure (Brown and Clasen, 2012).

The WHO CHOICE guideline suggests that any intervention that costs less than three times the per capita GDP per each ADALY is cost effective, and less than per capita GDP is very cost effective. Extending this premise, an ADALY in Rwanda may be valued at one to three times per capita GDP. The World Bank's estimated GDP in Rwanda in 2014 is $7.89 billion with a population of 11.34 million (The World Bank, 2016), yielding an estimated GDP/capita of approximately $696, or up to $2088 of value per ADALY. Using the lower bound of this interval, ADALY estimates associated with the cookstoves and water filters across five years are therefore conservatively estimated at over $11.80 million dollars over the 5 year lifetime of the program. To-date, there are no sales of ADALY health credits known to the authors, although a methodology for ADALY health credits associated with cookstoves has been registered with the Gold Standard. This methodology allows only the use of personal exposure measures and not cooking area emissions as used in this paper. However, as noted earlier the recent health impact evaluation of this program identified significant positive respiratory health impacts without identifying significant reductions in personal particulate matter exposure. Therefore, in our analysis we include the quantified and valued estimated health benefits associated with these cookstoves.

Table 1 below shows a summary of parameters used in this analysis.

3.8. *Impact analysis*

Fig. 1 summarizes the estimated impacts of the intervention. The total monetized benefit from the 5 year intervention is estimated over $66.67 million at approximately $655 per household, with over 87% of benefits attributable to the cookstoves. Fuelwood savings from both products account for the majority of total monetized benefits (65%), with 94% of fuelwood savings coming from the estimated 458,000 tons of fuelwood cost savings by the cookstove. Environmental impacts account for 10% ($6.94 million) of the benefits. Finally, benefits from time savings accounted for only 7% of total benefits, at least partly due to the low average wage in Rwanda (see Fig. 3).

3.9. *Cost-benefit ratios*

A CBR of 5.6 was calculated for the cookstove and water filter intervention. Overall, fuelwood savings was the primary contributor to the projected CBR. The price of fuelwood was also the primary contributor to variability in the results. Varying only the price of a wood bundle to the minimum reported price of $0.42 per bundle reduces the cost benefit ratio to 2.8 while valuing the fuelwood at the maximum price of $4.17 per bundle increases the cost benefit ratio to 9.4. We note that even with this and other important sensitivity analyses the CBR remains above 1, indicating the project benefits exceed its costs.

The value of labor provides the next most significant contribution, with the minimum reported cost of labor ($0.02/day) only reducing the CBR to 5.3 because of the already low $0.12 daily wage rate, but increasing the CBR to 8.1 based on the maximum reported cost of labor ($0.69/day). A similar result is seen with carbon credit pricing, with a CBR range of 5.5–7 based on minimum and maximum values due to the expected price of carbon being closer to the minimum value assessed.

We conducted a sensitivity analysis of the key model inputs, including: fuelwood price, labor value, carbon credit price, exclusive stove adoption in year 1, exclusive filter adoption in year 1, projected decrease in stove use per year, and projected decrease in filter use per year. As noted earlier, the stove and filter adoption parameters capture exclusive use as well as functionality of the products, and are therefore a combined parameter representing both proper functionality of the products and exclusive use by families. Table 2 below presents the nominal values used in the model, as well as the most conservative values and the most ambitious values. In the nominal case, the program has a total estimated cost-benefit ratio of 5.6. In the most conservative case, in which stove and filter use is assumed at only 50% in year 1, and decreases to no use within 2.5 years, the program breaks-even with a cost-benefit ratio of 1. In the most ambitious case, which assumes a high price for labor, fuelwood and carbon credits, and assumes exclusive use of products that are continuously maintained, the cost benefit ratio is over 16.

Table 1
Parameters used in analysis.

Parameter	Value	Units	Source
Project Size	101,778	households	Program records
Project Lifetime	5	years	Program records
Household Size	4.5	people	Household surveys
Stove Cost	$35.00	per household	Program records
Filter Cost	$40.00	per household	Program records
Recurrent cost	$7.00	per year	Program records
KPT Control	807.4	kg/person/year	KPT Tests
KPT Intervention	548.3	kg/person/year	KPT Tests
Initial product adoption	90.00%		Estimate
Product adoption decrease	10.00%	per year	Estimate
Weight of wood bundle	20.0	kg/bundle	KPT Survey
Price of wood bundle	$2.08		KPT Survey
Percentage of households that collect wood fuel	72.97%		KPT Survey
Time to collect one bundle	131.75	minutes/bundle	KPT Survey
Cost of labor	$0.12	$/hr	KPT Survey
Biomass Density	109.00	tons/ha	FAO - methods for estimating biomass density - Africa
Time to plant one hectare	277	person days/ha	KPT Survey
Trees per hectare	1350.00	trees/ha	Forest landscape restoration opportunity assessment for Rwanda
Cost of tree	$0.26	$/tree	KPT Survey
Percentage of wood species unusable for fuel	30%		Literature
Percentage of hhs boil at baseline	21.43%		Household Survey
Boiling wood usage	72.50	kg/person/year	Controlled Cooking Test
Time to boil water	402	minutes/person/year	Controlled Cooking Test
Quantity of purified water	7.15	liters/household/day	Verification Survey
Fraction served by public distribution or safe drinking water	0.83%		Verification Survey
Fraction of total cooking that continues to be done on baseline stove	15.46%		Verification Survey
Percentage of cooking done with pot skirt	94.28%		Verification Survey
Number of days filter is not working	0.77	days	Verification Survey
Number of days stove is not working	1.04	days	Verification Survey
Percentage that boils water after filtering	2.61%		Verification Survey
Quantity of purified water	1.59	liters/person/day	Calculated
Quantity of purified water	579.94	liters/person/year	Calculated
Carbon credit price	$5.40	$/tCO2	CarbonPulse (2015 estimate)

Table 3 presents the costs and projected benefits for each intervention, across fuelwood savings, time savings, environmental impacts, and health benefits for the nominal estimated values in our model.

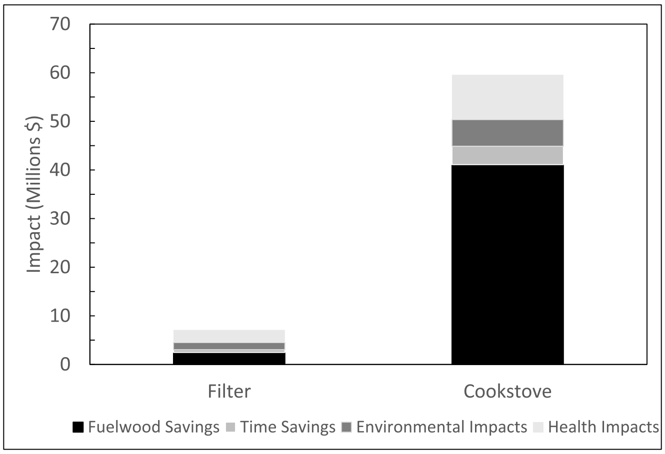

Fig. 3. Monetized benefits of water filters and improved cookstoves.

Table 2
Cost-benefit ratio sensitivity analysis.

	Estimated Value	Conservative Modeled Value	Ambitious Modeled Value
Fuelwood Price	$2.08	$0.42	$4.17
Labor Value	$0.12	$0.02	$0.69
Carbon Credit Price	$5.40	$1.00	$30.00
Stove Adoption Year 1	90%	50%	100%
Filter Adoption Year 1	90%	50%	100%
Filter Use Decrease/Year	10%	20%	0%
Stove Use Decrease/Year	10%	20%	0%
Cost-Benefit Ratio	5.6	1.0	16.1

Table 3
Estimated costs and benefits attributable to the water filters and cookstoves.

Impact Category	USD Benefit Per Household Over Project Lifetime	Total USD Benefit Over Project Lifetime	Total USD Costs Over Project Lifetime
Total Stoves	$585	$59.6M	$5.7M
Fuelwood Savings	$404	$41.1M	
Time Savings	$37	$3.8M	
Environmental Impacts	$54	$5.5M	
Health Benefits	$91	$9.2M	
Total Filters	$84	$8.6M	$6.2M
Fuelwood Savings	$24	$2.5M	
Time Savings	$6	$0.6M	
Environmental Impacts	$14	$1.5M	
Health Benefits	$25	$2.5	
Program Total	$655	$66.7M	$11.9M

4. Discussion

Previous improved cookstove and water treatment studies have reported similar CBRs as those estimated in this study. Evaluations of cookstove programs in Uganda (Habermehl, 2007), Malawi (Habermehl, 2008) and Mexico (García-Frapolli et al., 2010) reported CBRs ranging from 3 to 29. While two of three of these studies included an estimation of health benefits, all studies estimated fuelwood savings as the dominant contributor to the program benefits, similar to this study. A cost-benefit analysis of global interventions in the water supply and sanitation sector (Hutton et al., 2007b) reported CBRs from 4 to 32, with CBRs from 5 to 41 when providing universal basic access to improved water and sanitation as well as point of use water treatment through use of chlorine. While our sensitivity analysis provided a large range of potential CBRs, between around 1 to 16, the fuelwood price was the largest contributor to the uncertainty. However, little variance was measured between reported fuelwood pricing, and thus a high degree of certainty can be placed in this variable.

An estimated 458,000 tons of total fuelwood will be saved over the 5 year lifetime of the program, equating to approximately 4.50 tons per household. Fuelwood savings from the improved cookstove alone provide benefits almost four times the cost of the program, with the fuelwood savings from the water filter being the primary driver of water filter benefits. A 2013 study prepared by the Rwanda Ministry of Natural Resources examined the woodfuel supply and demand nationally. In the Western Province, the location of the intervention under study, the "business as usual" projected woodfuel demand in 2020 is about 1.165 million tonnes per year, while the supply is estimated as 1.058 million tonnes – an annual deficit of 106,000 tonnes, indicating an unsustainable deforestation rate absent mitigating interventions (Ministry of Natural Resources Rwanda, 2013). This study estimates 118,000 tonnes of annual woodfuel savings in the Western Province may be attributable to the program in year 1, decreasing to 65,000 tonnes in year 5. These estimates suggest that the woodfuel savings estimated as attributable to this program may compensate for the baseline woodfuel deficit in the region.

The value of labor was the next most significant variable mostly due to its inclusion in both the time saving and deforestation calculations. While time savings provide only 7% of the overall benefits, households who collect fuelwood are estimated to save approximately 48 days per year collecting fuelwood, while households who previously boiled may save approximately 23 days not performing the task of boiling water for drinking. These results indicate significant reductions in labor demand due to the interventions. The value of time is a debated topic, because of uncertainty in both how much time is actually converted to income generating activities and the actual value of the time. In this study, the majority of households reported using the additional time for income generating activities, which is why the reported wage rate is used to value time. Additionally, only the time collecting wood was quantified and no contributions from time saved cooking were quantified, thus the estimate is likely conservative. The value of labor was calculated based on reported wages from surveyed households instead of an average wage from the national income survey due to the lower economic status of the intervention households.

This program was designed to be financially sustainable through the generation and sale of carbon credits. The initial purchase of these products was privately funded, with carbon credits successfully generated and sold over the past several years. While the carbon credit price is not a large determinate in the CBR estimates, it is likely the most volatile of the variables. The value of carbon credits has decreased significantly over the past several years and continues to be unpredictable on both the voluntary and compliance markets. Unfortunately, the sales price achieved for these credits does not appear to be sufficient to ensure complete cost recovery. This intervention was delivered in 2014, and as of this publication, in 2019, most of the stoves and filters deployed should now be replaced, though there are no indications this will occur at scale. The implementer has worked to establish retail channels for these products, however the scale achieved over the five years since the programmatic distribution has not matched the clear needs or opportunities in Rwanda, and literature suggests that charging for health products may serve to increase barriers to use and programmatic costs without correlating to improved adoption (Kremer et al., 2011).

Recently, the results of the health impact trial associated with this intervention were published and indicated reduction in the prevalence of reported diarrhea and acute respiratory infection in children under 5 years old by 29% and 25%, respectively (Kirby et al., 2019b). Given that this program was deployed as a health intervention, these results are promising. However, the rocket-stove style cookstove used in this intervention has not demonstrated positive health impacts in other recent studies (Smith et al., 2011; Mortimer et al., 2017). These contradictory results suggest that the positive impact on respiratory disease may be attributable to the behavior change achieved by the implementer, or the reduction in disease achieved by the water filter may have had co-morbidity benefits (Kirby et al., 2019b). Irrespective of the potential health benefits of these types of stoves, the environmental benefits of the cookstoves through reduced woodfuel use are clearly illustrated in this paper. These considerable woodfuel savings estimates are independently a valuable impact.

Generally, the water filter provided few non-health benefits. In fact, when analyzing the model at a lower filter adoption rate the CBR increased because the savings in filter cost outweighed the reduction in benefits.

In addition to the environmental benefits estimated in this paper, there is an emerging alignment between monitored health impacts, calculations of units of heath impact (Averted Disability Adjusted Life Years – ADALYs), and, finally, monetized payments associated with demonstrated ADALYs. These estimates can provide additional input to cost-benefit evaluations. As noted above, the WHO CHOICE guideline suggests that any intervention that costs less than three times the per capita GDP per ADALY is cost effective. Generalized estimates of ADALYs generated from both diarrhea reduction and particulate matter personal exposure reduction among children under 5 suggest significant cost effective health benefits associated with the water filter intervention, potentially complementing the environmental impacts realized by the cookstoves (Thomas, 2016).

5. Conclusion

This paper establishes clear environmental benefits, in the form of woodfuel savings, and a positive cost-benefit ratio of the overall program. From a cost-benefit perspective, this study suggests that the cook stove and water filter interventions provide significant benefits, comparable to similar studies. Most significantly, this program may be effective for alleviating a regional woodfuel deficit. Even in the conservative case scenario modeled in the sensitivity analysis, the benefits still outweigh the total cost of the program. Fuelwood savings alone, mostly from improved cookstoves, provide substantial evidence to support implementation. However, while this study and many others have shown a positive benefit to cost relationship, the authors recognize that many variables within this study, specifically usage rates, are going to be program dependent and thus the results of this analysis are not necessarily transferrable to all improved cookstove or water filter interventions.

In this paper, we do not presume to weigh the environmental, health or time-savings benefits in a social or political frame. By illustration, while the environmental benefits are clearly greater with the cookstoves, the health benefits are more established with the water filter. And while time savings were not identified as a major monetized benefit, the social, educational and other downstream benefits of time savings may be of greater value in Rwanda than we were able to quantify in this study. Regardless, the modeled benefits show alignment between these interventions, across multiple dimensions. Since the initial design and deployment of this program, there has been increasing recognition in the global health community of the potential alignments between household water and sanitation interventions with air quality interventions both in terms of finding cost synergies and achieving greater health benefits (Clasen and Smith, 2019). This paper suggests that similar programs may further benefit from alignment of environmental and health interventions, and tying of multiple funding streams to these demonstrated benefits. While this intervention assumed revenue from carbon finance, a future program may be designed to ensure revenues tied to measured environmental and health benefits, in the form of health credits, development impact bonds, and government performance based contracting.

Declaration of competing interest

Authors Barstow, Silon and Thomas were compensated consultants to the funder, DelAgua Health during the course of this study. Their responsibilities include designing and delivering the intervention described. Authors Linden and Bluffstone were compensated researchers through grants provided by the funder, DelAgua Health, during the course of this study.

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