Quantification of Carbon Savings from Improved Biomass Cookstove Projects

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In spite of growing interest, a principal obstacle to wider inclusion of improved cookstove projects in carbon trading schemes has been the lack of accountability in estimating CO2-equivalent (CO2-e) savings. To demonstrate that robust estimates of CO2-e savings can be obtained at reasonable cost, an integrated approach of community-based subsampling of traditional and improved stoves in homes to estimate fuel consumption and greenhouse gas emissions, combined with spatially explicit community-based estimates of the fraction of nonrenewable biomass harvesting (fNRB), was used to estimate CO2-e savings for 603 homes with improved Patsari stoves in Purépecha communities of Michoacán, Mexico. Mean annual household CO2-e savings for CO2, CH4, CO, and nonmethane hydrocarbons were 3.9 tCO2-e home−1 yr−1 (95% CI ± 22%), and for Kyoto gases (CO2 and CH4) were 3.1 tCO2-e home−1 yr−1 (95% CI ± 26%), respectively, using a weighted mean fNRB harvesting of 39%. CO2-e savings ranged from 1.6 (95% CI ± 49%) to 7.5 (95% CI ± 17%) tCO2-e home−1 yr−1 for renewable and nonrenewable harvesting in individual communities, respectively. Since emission factors, fuel consumption, and fNRB each contribute significantly to the overall uncertainty in estimates of CO2-e savings, community-based assessment of all of these parameters is critical for robust estimates. Reporting overall uncertainty in the CO2-e savings estimates provides a mechanism for valuation of carbon offsets, which would promote better accounting that CO2-e savings had actually been achieved. Cost of CO2-e savings as a result of adoption of Patsari stoves was US$8 per tCO2-e based on initial stove costs, monitoring costs, and conservative stove adoption rates, which is ~4 times less expensive than use of carbon capture and storage from coal plants, and ~18 times less than solar power. The low relative cost of CO2-e abatement of improved stoves combined with substantial health co-benefits through reduction in indoor air pollution provides a strong rationale for targeting these less expensive carbon mitigation options, while providing substantial economic assistance for stove dissemination efforts.

Introduction

There is growing interest in trading carbon offsets from improved stove programs on carbon markets for voluntary reductions, or as part of the Clean Development Mechanism (CDM) of the Kyoto Protocol. This interest arises from the large number of people that still cook with biomass (approximately half of the global population) (1), and because emissions of greenhouse gases (GHGs) relative to delivered energy are high as a result of poor total energy efficiency of traditional stoves. There are three principal barriers to more widespread acceptance of carbon offsets from improved biomass cookstove projects. First, measurement and verification of emissions reductions are complex compared to the stack monitors typically used for industrial facilities, as stoves are spread over large areas, often in remote regions. Traditional assessment methods are also invasive and costly, requiring installation of vented hoods in homes while using sophisticated instrumentation, and typically provide only short-term estimates of emissions for a single meal event. Second, although in more commercial sectors direct reporting or fuel inventories are used to assess fuel consumption, cookstoves often rely on noncommercial or locally purchased fuels, and tracking of fuel consumption presents methodological and logistical challenges (2). Third, for biomass burning stoves, the tools to consistently estimate the fraction of nonrenewable biomass (fNRB) harvesting have been lacking. Consistent fNRB estimates are critical to accountability due to the magnitude of the difference in CO2-e-equivalent (CO2-e) savings between renewable and nonrenewable harvesting of fuelwood (3). As a result of these barriers, typical assessment methods for small-scale residential cookstove projects have made use of indoor air concentrations, rather than emissions, combined with default IPCC emission factors (4), or have used emissions factors from water boiling tests in simulated kitchens (5–7) which do not reflect daily cooking activities (8).

Given the increasing interest in carbon offset projects, and some adverse publicity over initial attempts to quantify offsets (9, 10), it has become increasingly clear that rigorous methods are required that will stand up to international scrutiny. Perhaps more importantly, successful trading of offsets from the residential sector on international markets is intrinsically linked to confidence in the estimates. Since the level of information available for each project will likely vary, the confidence bounds of CO2-e savings estimates will need to be explicitly defined, so that they may be reflected in carbon pricing. Unfortunately, however, IPCC default emission factors do not allow such computation, as uncertainty is not reported. Explicit reporting of confidence bounds of carbon offsets would provide a mechanism for inclusion of improved stove projects that have other positive economic, environmental, and health benefits in rural communities.

In the current paper CO2-e savings are assessed for 603 households that switch from traditional open fire stoves to...
improved Patsari stoves in the Meseta Purépecha region of central Mexico, using local community-based assessments of NRB combined with subsamples of emission factors and fuel consumption during daily cooking activities. Overall uncertainty associated with CO2-e savings estimates is evaluated in relation to both uncertainty and monitoring cost for optimization of subsampling design. Finally, net costs of making these CO2-e savings are compared to current carbon mitigation technologies in industrialized nations.

Methods

Study Area. The Patsari Stove Project is a long-term multi-institutional investigation of the health, climate, and social co-benefits of installation of Patsari stoves in communities in the Purépecha highlands of Michoacán in Central Mexico. Cooking in this region is typically performed on open fires surrounded by three stones or open fires with U-shaped surrounds built out of mud or clay. The Patsari was developed to mitigate indoor air pollution, to reduce fuelwood consumption, and to be acceptable and affordable to local populations (see Supporting Information for detailed information on the Patsari Stove). Most fuelwood harvesting in the Meseta Purépecha comes from forest areas and abandoned farming plots under regrowth, depending on population demand, with oaks as the preferred species. Fuelwood is typically collected for self-consumption by gathering on foot or with the help of pack animals, taking up to three or four hours daily.

Carbon Offset Estimation. Although calculation of carbon offsets involves combining multiple parameters, estimated using different methods, standard statistical approaches can be applied to propagate the uncertainty contributed by each component so that CO2-e savings and corresponding confidence intervals can be estimated from limited statistical samples of the larger population of homes with improved stoves. Thus using standard statistical criteria, CO2-e savings for the larger population can be estimated with 95% confidence bounds, after including variability associated with each step in the estimation: emissions measurements, fuel consumption, and the NRB harvesting. Estimation of the overall uncertainty in carbon offsets from improved biomass stove projects, although commonly applied in other fields and recommended by IPCC good practice guidelines (11), has not been performed for residential cookstove carbon offsets due to the lack of in-field community-based assessment of all parameters used in offset estimation. Estimation of Emission Reductions. Reductions in emissions of GHGs expressed in CO2-e home-1 yr-1 may be calculated as follows

\[
\Delta CO_2 e = \sum_{i=1}^{N} ((EF_Ri \times FC_i [1 - fNRB]) + (EF_NRi \times FC_i [fNRB])) - \sum_{j=1}^{N} ((EF_Rj \times FC_j [1 - fNRB]) + (EF_NRj \times FC_j [fNRB]))
\]

where EF is the emission factor in tCO2-e t-1 fuel consumed, FC is fuel consumption in t yr-1, and NRB is the fraction of nonrenewable biomass use. Emission factors assuming nonrenewable harvesting (EFNR) and renewable harvesting (EFR), which exclude CO2, are applied to the respective fraction of nonrenewable and renewable fuel consumption. The change in emissions is calculated on a per residence basis by summing emissions from all stoves used in homes with the improved stove (j) subtracted from the sum of emissions for all stoves used in homes with traditional stoves (i).

Estimation of Emission Factors. Emissions of GHGs were assessed in homes during normal cooking activities for a random sample of 8 open fire and 13 Patsari stoves. A full description of the emission factor sampling methodology and QA-QC is presented in Johnson et al. (8) and in the Supporting Information. Briefly, emission samples were collected over a full day of stove use into metal-coated multiple-layer Tedlar bags and analyzed for CO2, CH4, and total nonmethane hydrocarbons (TNMHCs) using a Perkin-Elmer 8410 gas chromatograph (Perkin-Elmer, US) with a flame ionization detector, and a nickel catalyst methanizer (SRI Instruments, USA). A 80–100 mesh Carbosphere packed stainless steel column (Waters Associated, Inc., US) was used for CO2, CO, and CH4 analysis, and a glass bead stainless steel column (Alltech, US) was used for TNMHC analysis.

CO2-e savings due to the lack of in-field community-based assessment of all parameters used in offset estimation is calculated as follows

\[
CO_2-e \text{ savings} = \sum_{i=1}^{N} ((EF_Ri \times FC_i [1 - fNRB]) + (EF_NRi \times FC_i [fNRB])) - \sum_{j=1}^{N} ((EF_Rj \times FC_j [1 - fNRB]) + (EF_NRj \times FC_j [fNRB]))
\]

Estimation of Uncertainties. Standard errors for emission factors, fuel consumption, and NRB used in the carbon reductions calculation (eq 1) were estimated with

\[
SE_i = \frac{SD_i}{\sqrt{N_i}}
\]

where SEi is the standard error, SDi is an estimate of the population standard deviation, and Ni is the sample size for each respective component. The variances and sample sizes for emission factors and fuel consumption are those reported by Johnson et al. (8) and Berrueta et al. (15) with fuel consumption data weighted to reflect 83% exclusive wood
users and 17% mixed wood/LPG users determined by tracking stove usage. The fNRB mean and standard deviation were derived by weighting the respective fNRB and variance for each of the 25 communities where the Patsaris were installed by the fraction of the 603 stoves in each community. Sample size for fNRB was determined as the number of homes in the fuel consumption subsample, where fNRB estimates were used to compute carbon savings (eq 1).

Propagations of error in estimates of CO2-e savings were determined using

$$SE_i = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial SE}{\partial x_i} SD_i \right)^2 / N_i}$$

(3)

where $SE_i$ is the standard error of the CO2-e savings and $x_i$ denotes the respective component in the CO2-e savings computation. 95% confidence intervals for CO2-e savings were then estimated using

$$\text{CO}_2\text{-e} \pm SE_i(1.96)$$

(4)

where $\text{CO}_2\text{-e}$ is the estimated CO2-e savings, $SE_i$ is the propagated standard error derived using eq 3, and 1.96 is the 0.975-quantile of the standard normal distribution. All terms were assumed independent, and thus covariance was not included in the standard error estimates of CO2-e savings (see Supporting Information). Estimation of the contribution of individual variables in eq 1 to the standard error of CO2-e estimates was computed by dividing the square of each component’s respective partial derivative by the sum of the squared partial derivatives.

Results

Figure 1 shows annual CO2-e savings with corresponding 95% confidence intervals for residences adopting an improved Patsari stove using locally assessed emissions factors, fuel consumption, and fNRB harvesting in local Purepecha communities (Table 1). Mean annual household CO2-e savings for the 603 homes with Patsaris were $3.9 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$ using the expanded set of GHG gases, and $3.1 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$ for the Kyoto set using a mean fNRB of 39%. Propagating the uncertainty from estimation of each component used to estimate CO2-e savings (eq 1) resulted in overall 95% confidence intervals around the mean CO2-e savings estimate of 22% (95% CI $0.9 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$) using the full set of GHG gases and 26% (95% CI $0.8 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$) using the more restricted set of Kyoto-sanctioned gases (CO2 and CH4). The majority of uncertainty in mean CO2-e savings using the full set of GHG gases was contributed by emission factors for open fires (12%), open fire fuel consumption (30%), and fNRB (48%).

Figure 1 shows CO2-e savings and 95% confidence intervals for the entire range of 0–100% nonrenewable harvesting, as fNRB in individual communities varies widely (0–90%) in the Meseta Purepecha where the improved Partsari stoves were disseminated. Thus for individual communities, mean CO2-e savings and corresponding 95% confidence intervals using the full set of GHG gases ranged from $1.6 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$ (95% CI $0.8 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$) for renewable harvesting to $7.5 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$ (95% CI $1.3 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$) for nonrenewable harvesting of fuelwood. Corresponding CO2-e savings and 95% CI using the Kyoto set of GHG gases ranged from $0.8 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$ (95% CI $0.7 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$) for renewable harvesting to $6.8 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$ (95% CI $1.2 \, \text{tCO}_2\text{-e home}^{-1} \text{yr}^{-1}$) for nonrenewable harvesting of fuelwood, respectively.

The relative contributions of emission factors, fuel consumption, and fNRB to overall uncertainty in CO2-e savings vary across the range of fNRB harvesting, illustrating how local community-based assessment of these compo-

![Figure 1. CO2-e savings and 95% confidence intervals for a shift from open fire to Patsari stoves using (a) the full GHG set (CO2, CO, CH4, and TNMHC) and (b) the Kyoto set (CO2 and CH4). Note: CO2-e project savings are 3.9 and 3.1 t home\(^{-1}\) yr\(^{-1}\) for the full and Kyoto GHG set, respectively.](image-url)
Discussion

Although CO₂-e reductions from small-scale household energy projects have been traded on voluntary markets, a principal criticism has been the lack of accountability and verification that CO₂-e savings have been achieved (9, 10). In part this has been because relatively noninvasive methods to verify emission reductions in homes during daily activities and methods for consistent spatially explicit community-based estimates of fNRB harvesting have been lacking. Equally critically, CO₂-e offsets have been reported without the corresponding uncertainty. Reporting the confidence intervals provides a quantitative measure of confidence in the CO₂-e savings, which shows significant potential to be used in their valuation. Since resolution and quality of information from individual projects are likely to differ, valuation of CO₂-e offsets based on the confidence bounds of the estimate provides a mechanism to reward organizations marketing offsets where more time and energy have been committed to verifying estimates, without excluding those where such information gathering is limited, but may provide valuable areas for carbon reduction. From a climate perspective, this would promote better accounting that CO₂-e savings had actually been achieved. Reporting the uncertainty in CO₂-e savings should therefore become standard for all carbon transactions to promote greater accountability. Given the financial sums potentially involved in carbon trading, verifying the confidence in the estimate will become more critical, particularly in preventing unscrupulous practices.

Typical assessment methods for small-scale carbon offset projects using default IPCC or laboratory-derived emission factors combined with regional estimates of fuelwood renewability can result in significant errors in CO₂-e savings. First, emissions factors derived from controlled water boiling tests in simulated kitchens did not reflect emissions from homes during daily cooking activities (8), which would result in a 64% underestimate of CO₂-e savings in the Meseta Purepécha (3). Variability in individual emissions factors is also not reported in current databases making it impossible to estimate uncertainty in overall CO₂-e savings (19). Use of emissions estimates not derived from local community-based sampling, even if measured in real homes during daily cooking activities, would still require broad assumptions about fuel types, cooking activities, and combustion efficiencies leaving aside variations as a result of altitude, seasonal, and meteorological factors. For emissions factors and fuel consumption, therefore, community-based data is critical in reducing uncertainty in CO₂-e savings estimates.

Similarly, use of regionwide fNRB estimates do not have sufficient resolution to determine the impact of fuelwood harvesting at the local scale required for carbon offset projects (17, 20). Regionwide estimates can lead to significant underestimation of fNRB harvesting (Figure 3), and thus significant errors when estimating CO₂-e savings in the Meseta Purepécha. The regional approach estimates a fuelwood supply and demand balance of 647 ± 785 kt yr⁻¹, while the community-based assessment estimates −117 ± 50 kt yr⁻¹. In general, regionwide approaches overestimate fuelwood supply, as they do not take into account nonaccessible areas, land ownership, and local topography, resulting in greater variability from less explicit land use and vegetation cover (16, 21). Since fNRB harvesting varies widely even between adjacent communities (Figure 2), and small-scale carbon offset projects in the household sector are not

### Table 1. Emissions Factors, Fuel Consumption, and fNRB Harvesting for Community-Based Samples in the Meseta Purepécha

<table>
<thead>
<tr>
<th>component</th>
<th>mean</th>
<th>SD</th>
<th>SE (% of mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>emission factors (tCO₂-e t⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>open fire nonrenewable</td>
<td>1.85</td>
<td>0.11</td>
<td>2</td>
</tr>
<tr>
<td>open fire renewable</td>
<td>0.32</td>
<td>0.10</td>
<td>11</td>
</tr>
<tr>
<td>Patsari nonrenewable*</td>
<td>1.72</td>
<td>0.09</td>
<td>1</td>
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<tr>
<td>Patsari renewable*</td>
<td>0.14</td>
<td>0.09</td>
<td>18</td>
</tr>
<tr>
<td>LPG*</td>
<td>3.34</td>
<td>0.07</td>
<td>&lt;1</td>
</tr>
<tr>
<td>fuel consumption (t home⁻¹yr⁻¹)c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>open fire (exclusive)</td>
<td>6.21</td>
<td>1.46</td>
<td>5</td>
</tr>
<tr>
<td>open fire (mixed)</td>
<td>4.20</td>
<td>2.01</td>
<td>11</td>
</tr>
<tr>
<td>Patsari (exclusive)</td>
<td>1.82</td>
<td>0.66</td>
<td>13</td>
</tr>
<tr>
<td>Patsari (mixed)</td>
<td>1.33</td>
<td>0.50</td>
<td>15</td>
</tr>
<tr>
<td>LPG (open fire home)</td>
<td>0.16</td>
<td>0.16</td>
<td>22</td>
</tr>
<tr>
<td>LPG (Patsari home)</td>
<td>0.06</td>
<td>0.06</td>
<td>30</td>
</tr>
<tr>
<td>fNRB (%)</td>
<td>na 39d</td>
<td>36</td>
<td>14</td>
</tr>
</tbody>
</table>

* Patsari mean emission factors and standard deviations are pooled from mud-cement and brick stove estimates (8).
+ Sample size, mean, and standard deviation are based on measurements performed by Smith et al. (14). c Fuel consumption per home was determined as the product of per capita fuel consumption and average household size for the 603 project homes. d fNRB in each of 25 individual communities was weighted by the numbers of improved stoves in each community to estimate CO₂-e savings.
equally distributed in all communities throughout a region, fNRB harvesting estimates should be based on community level assessment.

**Confidence in CO2-e Savings Estimates.** Using an integrated approach of community-based sampling of homes to estimate fuel consumption and emissions, combined with spatially explicit community-based estimates of fNRB harvesting, enables robust estimates of CO2-e savings. Use of the more constrained Kyoto GHG set resulted in a reduction of 21% in CO2-e savings relative to use of the full set of GHGs (Figure 1). Not including all major GHG gases significantly underestimates the overall emissions from both open fires and improved Patsari stoves due to the fraction of fuel carbon released as products of incomplete combustion. Although differences in CO2-e emissions estimates between the Kyoto and full GHG set are much smaller for centralized fossil fuel energy generation in industrialized nations where combustion efficiencies are much higher, for inefficient combustion in small-scale devices, the full range of GHGs should be included to avoid issues of incomplete accounting (22).

Since emissions factors, fuel consumption, and fNRB each contribute significantly to the overall uncertainty in estimates of CO2-e savings, community-based assessment of all of these parameters is critical for robust estimates. Given the differences observed between simulated tests and actual cooking practices, emissions testing in community settings using normal daily cooking activities is essential, especially with different fuels such as coal and charcoal. In addition, if large microclimatic differences are present within a project area resulting in shift in fuelwood species and combustion conditions, or there are large seasonal differences in fuel use or fuel moisture content, this variability should be incorporated into carbon offset estimates using additional sampling.

**Community-Based Sampling of Emission Factors and Fuel Consumption for CO2-e Savings Estimation.** Unlike the residential sectors of industrialized nations where CO2-e consumption can be assessed by combining commercial energy usage with stack-monitored emissions from central power generating facilities, measurement of solid fuel consumption and individual emissions from all homes in rural areas of developing nations is cost prohibitive given the large numbers of stoves and often remote areas involved.

FIGURE 2. Estimation of nonrenewable harvesting of fuelwood on a community basis in the Meseta Purépecha showing the large heterogeneity of harvesting between communities within relatively small spatial areas.

FIGURE 3. Difference between regionwide macroapproaches and community level estimates of fuelwood supply and demand compared for the study communities in the Meseta Purépecha. Note: error bars represent ±SE.
Estimating CO₂-e savings and corresponding confidence intervals for improved stove projects therefore involves sampling of fuel consumption and emissions factors from both traditional and improved stoves to obtain an estimate of both the central tendency and variability in the larger population of homes for which the CO₂-e savings are being estimated. The major barriers to field assessments for emission factors have been intrusive sampling hoods and sophisticated analytical methods required for analysis. Figure S2 (see Supporting Information) demonstrates that use of simple sampling probes for open fires stoves can be used comparably to constant flow sampling hoods (\( r^2 = 0.98, p < 0.001 \)) and that Patsari stoves with flues can be sampled directly, as fugitive emissions were a minor component of total emissions.

Confidence in CO₂-e savings for the larger population can be increased by monitoring larger samples, but a trade-off exists between increasing confidence in the CO₂-e savings and the added costs of monitoring more homes, especially if carbon trading pays for the costs of verification. Figure 4 shows the trade-off between cost and confidence in CO₂-e savings in relation to number of homes monitored for fuel consumption and emissions based on our experiences in Michoacán, Mexico. For comparison, INRB harvesting of 20% and 60% are included, which show similar trends, although areas with lower INRB would require larger sample sizes to achieve the same relative confidence in CO₂-e savings. While the magnitude of monitoring costs may vary between different groups and regions, the overall shape of the curve is likely to be similar and reflect similar tradeoffs. Based on these figures, the maximum benefit in confidence of CO₂-e savings for the lowest cost lies in sampling 25 homes each with open fires and with Patsaris, which would reduce the standard errors for emission factors and fuel consumption to less than 13%, giving a 95% confidence interval of ±19% around mean CO₂-e savings (an 14% reduction in uncertainty relative to the values in Figure 1). Although variability of fuel consumption and emissions in other project situations may differ, in the absence of better data these sample size estimates provide a reasonable starting point. Using these sample sizes, community-based assessment of fuel consumption, emissions, and the nonrenewable harvesting of fuelwood could be expected to cost as little as 7% of CO₂-e savings for a small-scale project (defined by CDM as less than 15 000 tCO₂-e yr⁻¹ of project emissions), assuming a carbon price of $7 per tCO₂-e, and a project time frame of 7 years used in current CDM methods.

**Carbon Mitigation Cost-Effectiveness.** Carbon prices for emission permits under a cap and trade system designed to meet Kyoto Protocol reduction targets have been estimated at US$26–159 and $53–68 per tCO₂-e for Europe and the United States, respectively (23). The costs of CO₂-e savings from adoption of Patsari stoves are approximately $4 per tCO₂-e given the full GHG set (~$5 per tCO₂-e using the Kyoto GHG set), nominal Patsari installation costs of $100, and 7-year time horizons for residential small-scale household energy projects outlined by the CDM. Not all improved stoves are adopted, however, as the transition to a new technology is moderated by practical and social factors. In addition, verification of CO₂-e savings incurs additional cost. Although these costs are much more variable on a project-by-project basis depending on stove promotion efforts and monitoring and verification strategies, incorporating a conservative minimum adoption rate of 60% within a community and monitoring costs from the Patsari Project increased costs to ~$8 per tCO₂-e saving. Even if these costs were three times higher, they would still be considerably less expensive than the lower range of CO₂-e abatement technology costs in Europe and the United States.

England’s Department for Business Enterprise and Regulatory Reform indicates nuclear and wind energy in England would be 9 and 15 times more expensive than the Patsari’s ~US$8 per tCO₂-e abated, respectively (24). Estimates by Sims et al. (25) indicate CO₂ capture from coal plants ($25–40) and solar power ($37–240) in the United States would be 3–5 and 7–30 times more expensive than Patsari dissemination. Should stripping CO₂ from the atmosphere be required, at a cost of $140–250 per tCO₂-e removed, this would be 17–31-fold more expensive than reducing CO₂-e emissions with improved stoves. The substantial health co-benefits in addition to the low relative cost of CO₂-e abatement using improved stoves provides a strong rationale for targeting these less expensive carbon mitigation options, especially for those sectors and technologies with relatively inelastic carbon emissions, while alternative low carbon emissions technologies are developed.

Sale of CO₂-e savings from improved stoves has the potential to significantly improve stove dissemination efforts in low-income rural communities through defrayment of stove dissemination costs. Carbon prices were ~US$30 per tCO₂-e for European Union allowances (EUA) and ~US$40 per tCO₂-e for voluntary offset programs (26, 27). Assuming a relatively conservative $7 per tCO₂-e within this range (reflecting what the project actually receives rather than the value of carbon sale), the 27 tCO₂-e saving over 7 years achieved by a Patsari would translate to approximately $190, considerably more than cost of stove materials and installation even when adjusting for minimum adoption rates and emissions monitoring expenses. While initial stove costs only represent a fraction of what is required in a successful stove dissemination project, these monetary benefits illustrate the potential of offset projects to boost improved cookstove dissemination efforts. Finally, the increased value of CO₂-e savings for communities with higher INRB would tend to focus offset projects in communities with greater resource constraints and environmental impacts, which may also favor improved stove adoption due to perceptions of fuel availability or cost.

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Supporting Information Available
Additional methodological information regarding the Patsari stove, independence of variables, emission factors, fuel consumption, NRB harvesting, and a simplified monitoring approach. This information is available free of charge via the Internet at http://pubs.acs.org.

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Supporting Information

Quantification of carbon savings from improved biomass cookstove projects

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The Patsari stove

The Patsari improved stove design is based on the Lorena cookstove that has been previously disseminated in Mexico, but with the following improvements: (a) optimized design of the combustion chamber and tunnels, (b) custom-designed parts for durability, including a metal chimney support and a ceramic stove entrance; and (c) reduction in construction time and standardized inner dimensions. The Patsari has a combustion chamber with an opening for fuelwood and a metal “comal” 52 cm in diameter (a flat surface on which tortillas are cooked), which is sealed to avoid fugitive smoke emissions. Emissions are vented through tunnels that conduct the combustion gases to secondary chambers with smaller comales for low power tasks. The mud–cement and brick Patsari were used in this study as they are the most common models (see Figure S1). All the materials for the Patsari are available locally and custom-made stove parts are manufactured by small local industries.

Patsari dissemination and monitoring

Patsaris have been disseminated mainly in the Meseta Purépech by GIRA A.C., a local NGO promoting rural development, with additional dissemination efforts in central Mexico and eight other Mexican states. Field trials and field monitoring within communities were conducted to provide direct feedback in a cyclic process to both the stove design and the stove dissemination process through communities. To monitor the adoption process in communities, GIRA records all Patsari stoves installed in an electronic data base including relevant data on stove construction as well as aspects related to stove adoption such as actual stove and fuel usage patterns, maintenance and repair actions. The Patsari Project is a long-term multi-institutional investigation of the health, climate and social co-benefits of installation of Patsari stoves in communities in the Purépecha highlands of Michoacán in Central Mexico. The Patsari’s co-benefits have been studied comprehensively, including assessments of health impacts (1), reductions in indoor air pollution (2-4), stove performance (5), social perceptions (6, 7), impacts on fuelwood renewability (8, 9), and emission factors (10).
Independence of variables in CO$_2$-e savings computation

The low correlations (Pearson r<0.33) in Table S1 indicate there was no significant covariance for variables used in carbon offset estimation in the Meseta Purépecha. Fuel consumption, fNRB, and CO$_2$/(CO$_2$+CO) ratios (a proxy for emission factors – see Table S2), were collected during a stove performance study in 15 open fire homes and 23 Patsari homes in 5 villages across the Meseta Purépecha.

Table S1: Covariance matrix for per capita fuel consumption, fNRB, and CO$_2$/(CO$_2$+CO) ratios.

<table>
<thead>
<tr>
<th></th>
<th>Open fire CO$_2$/(CO$_2$+CO) (N=15)</th>
<th>Open fire fuel consumption (N=15)</th>
<th>Patsari CO$_2$/(CO$_2$+CO) (N=23)</th>
<th>Patsari fuel consumption (N=23)</th>
<th>fNRB (N=38)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open fire CO$_2$/(CO$_2$+CO) (N=15)</td>
<td>Pearson r</td>
<td>1</td>
<td>0.23</td>
<td>(a)</td>
<td>(a)</td>
</tr>
<tr>
<td></td>
<td>Sig.</td>
<td></td>
<td>0.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open fire fuel consumption (N=15)</td>
<td>Pearson r</td>
<td>0.23</td>
<td>1</td>
<td>(a)</td>
<td>(a)</td>
</tr>
<tr>
<td></td>
<td>Sig.</td>
<td>0.49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patsari CO$_2$/(CO$_2$+CO) (N=23)</td>
<td>Pearson r</td>
<td>(a)</td>
<td>(a)</td>
<td>1</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Sig.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patsari fuel Consumption (N=23)</td>
<td>Pearson r</td>
<td>(a)</td>
<td>(a)</td>
<td>0.33</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Sig.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fNRB (N=38)</td>
<td>Pearson r</td>
<td>0.28</td>
<td>-0.28</td>
<td>-0.31</td>
<td>-0.31</td>
</tr>
<tr>
<td></td>
<td>Sig.</td>
<td>0.35</td>
<td>0.38</td>
<td>0.17</td>
<td>0.22</td>
</tr>
</tbody>
</table>

(a) No comparison is possible as open fires and Patsari stoves are in different homes.
Emission factor assessment

Open fire emissions sampling
Open fire emissions were collected from a probe inserted into the center of a portable hood’s exhaust flue. The portable hood was constructed of stainless steel, measuring 1x1m at the base and a flame proof skirt was draped around three sides of the stove to minimize fugitive emissions. A small metal fan exhausted emissions, resulting in a face velocity of 0.11 m s\(^{-1}\) and flue velocity of 6.2 m s\(^{-1}\). Prior studies using emission hoods found no change in combustion efficiency at higher face velocities (11, 12).

Patsari emissions sampling
Pastari emission samples were collected from a probe inserted 70 cm above the stovetop. While minor fugitive emissions may have escaped from the stove opening during sampling, the draw of the chimney captured the vast majority of emissions. In addition Zhang et al. (13) reported no difference in emissions ratios when sampling directly from a vented stove flue or from a hood placed over the entire vented stove.

Emission samples
Emissions were sampled into a 100 L light-shielded Tedlar bag (SKC Inc, USA) with an SKC universal pump (model 224-PCXR8, SKC Inc., USA) at a flow rate of 0.86 L min\(^{-1}\). Following the sampling period, approximately 2-3 liters of the initial sample in the Tedlar bag was transferred to a 5 L metal-coated multiple-layer Tedlar (MMT) bag, which maintain stability of CO\(_2\), CO, CH\(_4\), and total hydrocarbons for at least three months (14), until gas chromatography analysis was conducted. CO\(_2\), CO, CH\(_4\), and total non-methane hydrocarbons (TNMHC) were quantified using a Perkin-Elmer 8410 gas chromatograph (Perkin-Elmer,USA) with a flame ionization detector, and a nickel catalyst methanizer (SRI Instruments, USA). A 80-100 mesh Carbosphere\textsuperscript{®} packed stainless steel column (Waters Associated, Inc., USA) was used for CO\(_2\), CO and CH\(_4\) analysis and a glass bead stainless steel column (Alltech, USA) was used for TNMHC analysis.
Seven point calibration curves were made to quantify the sample gases using dilutions of a NIST traceable gas standard mixture of CO$_2$, CO, and CH$_4$ in a helium balance (Scott Specialty Gases, USA). TNMHC was calculated by subtracting CH$_4$ from the THC (measured as CH$_4$). All calibration curves had r$^2$ values exceeding 0.99 and a standard injection was conducted before and after each sample batch (10-20 samples) to ensure consistent response. All standard responses were within 10% of the respective calibration point with coefficients of variation of 3.9, 3.7, and 2.1% for CO$_2$, CO, and CH$_4$, respectively. Twenty percent (n=14) of the CO$_2$, CO, and CH$_4$, and 28% (N=20) of the THC samples were randomly selected for repeat analysis and all were within 10% of the initial sample with a coefficient of variation of 2.5, 1.5, and 2.8% for CO$_2$, CO, and CH$_4$, respectively, and 2.2% for THC.

**Carbon Balance**

The carbon balance was developed by Crutzen et al. (15) for determination of large scale biomass fire emissions and has been commonly employed in stove emissions studies (11, 13, 16-20). The carbon balance requires only a representative emission sample and determination of the total emitted carbon.

Total emitted carbon was determined as follows:

$$C_T = C_F - C_A$$  \(\text{(S1)}\)

where $C_T$ is the total emitted carbon, $C_F$ is the carbon in the fuel before the test, and $C_A$ is the remaining ash and char carbon after the test is completed. Fuel carbon was measured by weighing the fuel before and after the sampling period and a small sample (~200g) from each test batch was massed before and after a 24 hour period in a 105°C electric oven to subtract moisture content. On a dry basis, it was assumed the carbon content of the fuel wood to be 50%, which is fairly uniform among pine and oak (21).

To derive emission ratios, first the total carbon in the emission sample is determined as,

$$C_S = C_{CO_2} + C_{CO} + C_{CH_4} + C_{TNMHC} + C_{TSP}$$  \(\text{(S2)}\)

where $C_S$ is the total carbon in the emissions sample and $C_{CO_2}$, $C_{CO}$…$C_{TSP}$ are the carbon masses from each emission species in the sample. Particulate carbon content was estimated from quartz filters sent to Sunset Laboratories (Tigard, OR, USA) for EC/OC analysis using the Thermal
Optical method (NIOSH 5040). The ratio of the carbon in an emission species ($C_{Xi}$) to the total carbon in the sample ($C_s$) was then applied to the total emitted carbon from equation S1 ($C_T$) to determine the total amount of each species:

$$C_T \left( \frac{C_{Xi}}{C_s} \right) = C_{Xi} \quad (S3)$$

where $C_{Xi}$ is the emitted carbon for a respective emission species. The total carbon emission as each species was then divided by the total fuel consumption to determine each respective emission factor.

**Converting emission species to CO$_2$-equivalent**

CO$_2$-e per kilogram fuelwood were calculated using the following:

$$\text{CO}_2\text{-e} = \sum \text{GWP}_i \times \text{GHG}_i \quad (S4)$$

where GWP$_i$ is the 100 year global warming potential and GHG$_i$ is the quantity of each GHG. CO$_2$ and CH$_4$ GWPs (1 and 25, respectively) are published in the IPCC’s 2007 Fourth Assessment Report and those used for CO and TNMHC (3 and 11, respectively) are from the IPCC’s 1990 First Assessment Report. CO and TNMHC GWPs were not included in later IPCC reports due to uncertainty in their radiative forcing, although CO extends the life of other GHGs by providing the primary atmospheric sink for OH.
Simplified emission monitoring methods

Monitoring in rural homes rather than simulated kitchens

A principal reason why previous emission factors were derived in simulated kitchens rather than in rural homes was the need for intrusive and cumbersome constant flow sampling hoods (11, 13, 17, 22) to control for dilution effects of room air on gas concentrations in the plume. Emissions measurements that have been conducted in homes have typically consisted of one cooking event and focused on specific emission species rather than comprehensive GHG assessment due to the complex and intrusive equipment (18, 19). Removal of this barrier greatly facilitates the measurement of representative emissions factors from homes in communities during normal daily cooking activities. To demonstrate that a simple probe could replace these sampling hoods, CO$_2$/($CO_2$+CO) ratios monitored using a 3-pronged probe that hung directly above an open fire were compared against CO$_2$/($CO_2$+CO) ratios measured with a constant flow sampling hood. Samples were taken at 30 second intervals alternating between the hood and probe for three separate open fires (Figure S2).

Figure S2. Correlation between CO$_2$/($CO_2$+CO) ratios using a constant flow sampling hood and using a probe suspended above the fire.

Figure S2 shows the relationship between CO$_2$/($CO_2$+CO) ratios monitored using a 3-pronged probe that hung directly above an open fire compared against CO$_2$/($CO_2$+CO) ratios measured with a constant flow sampling hood for three open fires, and the relative uncertainty introduced
by these estimates. Correlation between CO₂/(CO₂+CO) ratios had an \( r^2 \) of 0.98 (\( p<0.001 \)), with a slope of 0.98, demonstrating excellent agreement between the measures. Thus a simple probe can be used instead of the complex emissions hoods that have been a barrier to more extensive field based measurements during normal daily cooking activities.

_Simplified monitoring procedures using CO₂/(CO₂+CO) ratios_

If emission assessments are to be further simplified for follow-up in successive carbon marketing cycles (in current CDM methods CO₂-e is sold for a 7 year period), as a performance indicator during stove design, or as an assessment tool for non-specialist groups, approaches that do not involve the complex analytical requirements of previous emissions assessments are required. Since the relative emissions of individual GHG species for a given fuel type are largely determined by combustion efficiency, based on approaches developed by Edwards et al. (23), the CO₂/(CO₂+CO) ratio, for which a variety of relatively low cost real-time instrumentation exists, was evaluated as a proxy for nominal combustion efficiency (NCE) (the fraction of fuel carbon converted to CO₂). This approach was evaluated by simultaneously monitoring CO and CO₂ concentrations with a flue gas analyzer (Autologic, USA) in the homes in which the gas chromatography analysis was conducted (Figure S3). The instrument was calibrated with NIST-traceable CO and CO₂ reference gas (Scott Specialty Gases, USA) and background concentrations were accounted for by zeroing the unit in room air for a minimum of 5 minutes before and after sampling.
Figure S3. CO$_2$/($CO_2$+CO) ratio as a predictor for NCE as measured by gas chromatography.

Figure S3 shows the relationship between CO$_2$/($CO_2$+CO) ratio using portable commercial instruments that do not involve complex analytical requirements and NCE determined with gas chromatography. The correlation between NCE and CO$_2$/($CO_2$+CO) ratio had an $r^2$ of 0.98 (p<0.001) for open fires and 0.94 (p<0.001) for Patsaris, demonstrating that the CO$_2$/($CO_2$+CO) ratio was a good proxy for NCE for the fuels used in these homes. Since relative amounts of products of incomplete combustion (PICs) and thus CO$_2$-e emissions are related to NCEs, Table S2 shows CO$_2$/($CO_2$+CO) ratios can predict CO$_2$-e emissions. Char is also included as a predictor for nonrenewable models because each gram of fuel that is converted to char negates a gram of fuel from being emitted as CO$_2$ or PICs, of which ~90% of fuel carbon or greater is emitted as CO$_2$. Since CO$_2$ is the largest contributor to CO$_2$-e emissions for nonrenewable fuel use, and excluded from CO$_2$-e emissions for renewable fuel use, char production is only a significant predictor for nonrenewable scenarios.
<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Adjusted R²</th>
<th>Predictors</th>
<th>N</th>
<th>B</th>
<th>Std. Error</th>
<th>Std. β</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full</td>
<td>Kyoto</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open fire CO₂-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>equivalent kg⁻¹</td>
<td>0.98</td>
<td>0.93</td>
<td>14</td>
<td>6533</td>
<td>2829</td>
<td>692</td>
<td>954</td>
</tr>
<tr>
<td>(nonrenewable)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patsari CO₂-</td>
<td>0.96</td>
<td>0.98</td>
<td>25</td>
<td>6177</td>
<td>1380</td>
<td>202</td>
<td>146</td>
</tr>
<tr>
<td>equivalent kg⁻¹</td>
<td>(nonrenewable)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open fire CO₂-</td>
<td>0.91</td>
<td>0.65</td>
<td>14</td>
<td>6567</td>
<td>3237</td>
<td>564</td>
<td>660</td>
</tr>
<tr>
<td>equivalent kg⁻¹</td>
<td>(renewable)</td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patsari CO₂-</td>
<td>0.96</td>
<td>0.90</td>
<td>25</td>
<td>5547</td>
<td>1837</td>
<td>235</td>
<td>119</td>
</tr>
<tr>
<td>equivalent kg⁻¹</td>
<td>(renewable)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model predictions had r² values ranging from 0.91-0.98 for the full GHG set, but were slightly lower (0.65-0.98) for the more restricted Kyoto gases and renewable harvesting. The largest increase in uncertainty occurs for 0% fNRB under the Kyoto set, when the renewable open fire emission factor, which has a relatively low r² value of 0.65, contributes 46% of the uncertainty in CO₂-e savings (see Figure 1). Uncertainty introduced by these models resulted in a 1% and 4% increase in 95% confidence intervals of CO₂-e savings, using the full and Kyoto GHG set, respectively. Since the relationship between the CO₂/(CO₂+CO) ratio and products of incomplete combustion varied between the open fire and Patsari, and may also vary depending on fuel type, fuel moisture content, local cooking practices, amongst other factors, use of the CO₂/(CO₂+CO) ratio to estimate emissions requires calibration in local community settings. Thus this approach is perhaps better suited as an inexpensive verification tool for CO₂-e savings in successive time periods after initial verification with direct monitoring of GHG emissions.

**Laboratory versus field based assessment for stove emissions**

Use of laboratory-based emission factors can produce substantial errors in stove emission estimates (24) as they do not reflect those occurring in homes during normal stove use. For
example, NCE for open fires has been consistently overestimated by laboratory testing. CO/CO$_2$ ratios, which are a good proxy for combustion efficiency (Figure S3), have been reported to be higher for open fire wood-burning stoves by Johnson et al. (10), Ludwig et al. (18), and Kituyi et al. (19), than those measured during controlled water boiling tests (WBTs) in a laboratory setting by Johnson et al. (10), Bhattacharya et al. (17), or Smith et al. (11) and Zhang et al. (13) (see Figure S4). Roden et al. (25) also reports higher CO and PM emission factors for in-home measurements of open fires relative to during WBTs. Further, improved stove combustion efficiency will vary for each stove project and differences between in-home stove use and during controlled tests are largely unknown and difficult to predict due to the variability in stove design and fuel type. In the case of the Patstari, NCE was underestimated during WBTs relative to in-home stove use, indicating the WBT penalized the improved stove while the open fire appeared more efficient than its true performance.

Figure S4. CO/CO$_2$ ratio comparison between in-home assessments during normal cooking and during WBTs for open fire wood-burning stoves.
**Fraction of nonrenewable biomass method information**

The fraction of fuelwood extracted on a nonrenewable basis was estimated based on the following equation:

\[
f_{NRB_v} = \left[ \frac{FWS_v - C_1}{C_1} \right] \quad (S5)
\]

Where \( f_{NRB_v} \) is the fraction of fuelwood extracted on a nonrenewable basis per accessible area “v” for each community, \( FWS_v \) is the sustainable fuelwood supply in area “v” and \( C_1 \) is the fuelwood consumption per community in t yr\(^{-1}\) (dry matter).

**Fuelwood supply (FWS)**

The fuelwood supply capacity of an area is a function of: (a) fuelwood stocks and productivity in natural and man-made landscapes; (b) land cover changes, which indirectly affect fuelwood availability; and (c) access to fuelwood (26-28). The annual fuelwood increment, which can be sustainably harvested from each locality accessible area was estimated using the following equation:

\[
FWS_v = \sum_{j=1}^{8} (A_{vj} \times P_j) \quad (S6)
\]

where \( A_{vj} \) is each community’s accessible area “v” by land cover “j” in ha and \( P_j \) is the fuelwood productivity by land cover class “j” in t ha\(^{-1}\) yr\(^{-1}\) (dry matter).

Accessible areas around individual localities \( A_{vj} \) were defined as the area from which fuelwood gatherers obtain fuelwood (i.e. the woodfuel-shed, given means of transport and daily time available for collecting and transporting fuelwood). These areas were estimated based on cost-distance maps, where each pixel or cell represents the time needed for a walking person to walk through it. Walking speeds were calculated as the product of a friction variable relating to slope of the terrain; an attraction variable relating to distribution and preference of vegetation species; natural barriers such as lakes and rivers; and local passages in the form of bridges, tunnels and dams. A walking fuelwood gatherer may therefore spend up to 3-4 hours (round trip) for harvesting fuelwood within the accessible area based on local surveys (8).
Fuelwood productivity $P_j$ estimates by land cover class (Table S3) were derived from the study by Ordoñez et al. (29) conducted over the Meseta Purépecha during 2000, in which the carbon content in vegetation, litter and soil was estimated by field measurement, allometric equations and collection of samples. Equation S7 shows how the above ground carbon content of trees and shrubs was converted into an annual woody biomass increment suitable as fuelwood.

$$P_j = \frac{B_j \times 2 \times Ff_j}{t_j} \quad (S7)$$

where $B_j$ is the carbon content in the aboveground portion of trees and shrubs by land cover class “j” in Mg ha$^{-1}$; 2 is the ratio between carbon and biomass (dry matter); $Ff_j$ is the fuelwood fraction (aboveground biomass suitable as fuelwood) by land cover class “j”; and $t_j$ is the average time needed to reach the aboveground biomass stock in years. Note that $B_j \times 2/t_j$ correspond to the mean annual increment (MAI) by land cover class.

Table S3. Fuelwood productivity estimates linked to land cover classes.

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>Aboveground biomass stock in Mg ha$^{-1}$ (b)</th>
<th>Average time needed to reach aboveground biomass stock in years</th>
<th>Mean Annual Increment (MAI) in Mg ha$^{-1}$ yr$^{-1}$</th>
<th>MAI as a percentage of aboveground biomass stock</th>
<th>Fuelwood to aboveground biomass ratio (Ff) (g)</th>
<th>Fuelwood increment in Mg ha$^{-1}$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture$^2$</td>
<td>15 ± 15</td>
<td>30 ± 8 (c)</td>
<td>0.5 ± 0.5</td>
<td>3%</td>
<td>0.2</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Secondary forests</td>
<td>145 ± 8</td>
<td>25 ± 6 (d)</td>
<td>7.3 ± 1.9</td>
<td>4%</td>
<td>0.6</td>
<td>3.5 ± 0.9</td>
</tr>
<tr>
<td>Fir forests</td>
<td>269 ± 30</td>
<td>45 ± 11 (e)</td>
<td>9.0 ± 2.4</td>
<td>2%</td>
<td>0.4</td>
<td>2.4 ± 0.7</td>
</tr>
<tr>
<td>Grasslands</td>
<td>15 ± 15</td>
<td>30 ± 8 (c)</td>
<td>0.5 ± 0.5</td>
<td>3%</td>
<td>0.2</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Oak forests</td>
<td>226 ± 22</td>
<td>60 ± 15 (f)</td>
<td>4.5 ± 1.2</td>
<td>2%</td>
<td>0.8</td>
<td>3.0 ± 0.8</td>
</tr>
<tr>
<td>Pine forests</td>
<td>201 ± 21</td>
<td>40 ± 10 (d)</td>
<td>6.7 ± 1.8</td>
<td>3%</td>
<td>0.4</td>
<td>2.0 ± 0.5</td>
</tr>
<tr>
<td>Pine-Oak forests</td>
<td>183 ± 18</td>
<td>50 ± 13 (d)</td>
<td>4.6 ± 1.2</td>
<td>2%</td>
<td>0.6</td>
<td>2.2 ± 0.6</td>
</tr>
<tr>
<td>Shrublands</td>
<td>57 ± 50</td>
<td>40 ± 10 (d)</td>
<td>1.9 ± 1.7</td>
<td>3%</td>
<td>0.8</td>
<td>1.1 ± 1.0</td>
</tr>
</tbody>
</table>

Notes: (a) rainfed or seasonally cultivated agriculture. 
(b) From Ordoñez et al. (29). 
(c) Average age of trees outside forests from field-based estimates in the Meseta Purépecha. 
(d) From Návar et al. (30); 
(e) From The National Forestry Inventory (31); 
(f) From Bonfil (32); 
(g) The Ff coefficient integrates two ratios:1) woody biomass to total biomass and 2) fuelwood to woody biomass (33-37).
Fuelwood demand

Fuelwood consumption in dry matter was measured in the Meseta Purépecha by Berrueta et al. (5) using the kitchen performance test (KPT). The KPT is a field-based test, which evaluates stove performance in homes where daily fuel use and cooking tasks are monitored in community households. 23 households exclusively using fuelwood were randomly selected randomly in two communities of the Meseta Purépecha: Comachuen and La Mohonera. 20 additional households in these communities that used a combination of fuelwood and LPG were also selected. In all households oak and pine were main fuelwoods used.

The KPT was performed in three phases. First, a baseline when the family used an open fire stove [dry season], followed by an intermediate phase 6 months after installation of the improved Patsari stove [rainy season], and a final phase after 1 year of use [dry season].

The daily consumption of LPG and fuelwood was monitored daily for one week and the number of people for whom food was prepared at each meal was recorded, differentiated by sex and age. An equivalence factor called a “standard adult,” which relates the fractional food requirement in energy needs into that of an adult male of reproductive age, based on the following ratios: Child: 0-14 years, 0.5; Female: over 14 years, 0.8; Male: 15-59 years, 1.0; Male: over 59 years, 0.8 (38). Food is not cooked for domestic animals in Mexico and thus was not incorporated into determination of per capita fuel consumption. Fuelwood was not provided to families to minimize potential bias in fuel consumption. In Phase 2 and 3, it was common that Patsaris and traditional cookstoves were used in the same homes.

Fuelwood consumption by locality was estimated based on the following equation:

\[ C_l = (U_l \cdot FC) + (M_l \cdot FCM) \]  \hspace{1cm} (S8)

where \( C_l \) is the fuelwood consumption per community “l”, in Mg yr\(^{-1}\) (dry matter); FC and FCM are the average per capita fuelwood consumption in the Meseta Purépecha for exclusive wood (FC) and mixed wood/LPG (FCM) users in Mg yr\(^{-1}\) cap\(^{-1}\) (dry matter); U is the number of exclusive fuelwood users per community “l” and M represents mixed users per community “l.”
Small sample sizes

Though sample sizes for the individual components used in calculating CO$_2$-e savings are relatively small, a normal distribution was assumed in determining confidence intervals to comply with other global approaches for assessment of carbon savings, as is recommended by the IPCC’s Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (39). IPCC’s Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories recommends assuming a normal distribution as a first choice. Furthermore, use of the more conservative t-distribution would increase 95% confidence intervals by 0.04 tCO$_2$-e yr$^{-1}$ home$^{-1}$, representing a 0.9% increase relative to mean CO$_2$-e savings for the Meseta Purépecha.
References


38. Openshaw, K. *Wood fuel surveys*; UN Food and Agriculture Organization: 1983.