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).

Figure S1: From left to right, traditional open fire, mud-cement Patsari, and brick Patsari.

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.

		Open fire $CO_2/(CO_2+CO)$ (N=15)	Open fire fuel consumption (N=15)	Patsari $CO_2/(CO_2+CO)$ (N=23)	Patsari fuel consumption (N=23)	fNRB (N=38)
Open fire $CO_2/(CO_2+CO)$ (N=15)	Pearson r	1	0.23	(a)	(a)	0.28
	Sig.		0.49			0.35
Open fire fuel consumption (N=15)	Pearson r	0.23	1	(a)	(a)	-0.28
	Sig.	0.49				0.38
Patsari $CO_2/(CO_2+CO)$ (N=23)	Pearson r	(a)	(a)	1	0.33	-0.31
	Sig.				0.21	0.17
Patsari fuel Consumption (N=23)	Pearson r	(a)	(a)	0.33	1	-0.31
	Sig.			0.21		0.22
fNRB (N=38)	Pearson r	0.28	-0.28	-0.31	-0.31	1
	Sig.	0.35	0.38	0.17	0.22	

(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® 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:

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

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 105ºC 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,

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

where C_S is the total carbon in the emissions sample and C_{CO_2}, $C_{CO} \ldots C_{TSP}$ 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_{X_i}) 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:

$$C_T\left(\frac{C_{X_i}}{C_S}\right) = C_{X_T} \qquad \text{(S3)}$$

where C_{X_T} 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:

$$CO_2\text{-e} = \sum GWP_i \times GHG_i \qquad \text{(S4)}$$

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.

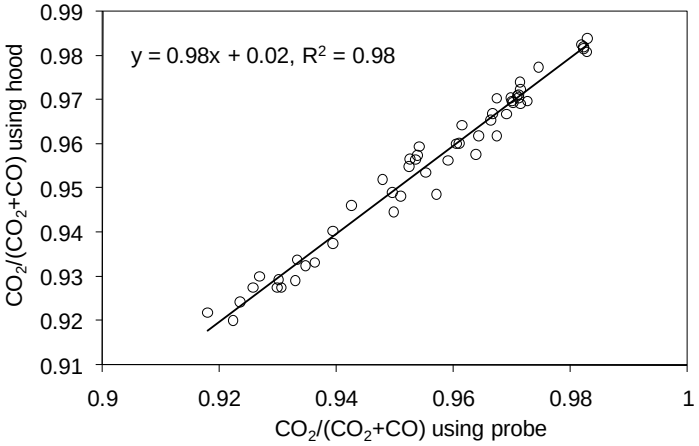


Figure S2 shows the relationship between $CO_2/(CO_2+CO)$ ratios monitored using a 3-pronged probe that hung directly above an open fire compared against $CO_2/(CO_2+CO)$ ratios measured with a constant flow sampling hood for three open fires, and the relative uncertainty introduced

by these estimates. Correlation between $CO_2/(CO_2+CO)$ 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 $CO_2/(CO_2+CO)$ ratios

If emission assessments are to be further simplified for follow-up in successive carbon marketing cycles (in current CDM methods CO_2-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 $CO_2/(CO_2+CO)$ 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 CO_2). This approach was evaluated by simultaneously monitoring CO and CO_2 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 CO_2 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.

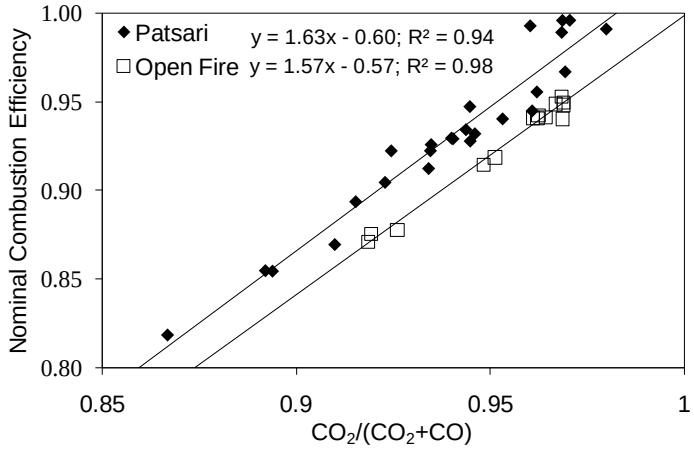


Figure S3 shows the relationship between $CO_2/(CO_2+CO)$ ratio using portable commercial instruments that do not involve complex analytical requirements and NCE determined with gas chromatography. The correlation between NCE and $CO_2/(CO_2+CO)$ ratio had an r^2 of 0.98 ($p<0.001$) for open fires and 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 S2. Use of $CO_2/(CO_2+CO)$ ratios and char kg^{-1} to predict CO_2-e emissions for the full GHG set (CO_2, CH_4, CO, TNMHC) and the Kyoto set (CO_2, CH_4).

Dependent Variable	Adjusted R^2		Predictors	N	B		Std. Error		Std. β		Sig.	
	Full	Kyoto			Full	Kyoto	Full	Kyoto	Full	Kyoto	Full	Kyoto
Open fire CO_2-equivalent kg^{-1} (nonrenewable)	0.98	0.93	Constant	14	6533	2829	692	954	-	-	<0.001	0.013
			Char kg^{-1}		-4	-3	0.3	0.4	-0.72	-0.88	<0.001	<0.001
			$CO_2/(CO_2+CO)$		-4699	-1079	744	1025	-0.35	-0.12	<0.001	0.032
Patsari CO_2-equivalent kg^{-1} (nonrenewable)	0.96	0.98	Constant	25	6177	1380	202	146	-	-	<0.001	<0.001
			Char kg^{-1}		-3	-4	0.2	0.1	-0.85	-0.95	<0.001	<0.001
			$CO_2/(CO_2+CO)$		-4470	-441	209	151	-0.88	-0.09	<0.001	0.008
Open fire CO_2-equivalent kg^{-1} (renewable)	0.91	0.65	Constant	14	6567	3237	564	660	-	-	<0.001	<0.001
			$CO_2/(CO_2+CO)$		-6622	-3275	591	691	-0.96	-0.81	<0.001	<0.001
Patsari CO_2-equivalent kg^{-1} (renewable)	0.96	0.90	Constant	25	5547	1837	235	119	-	-	<0.001	<0.001
			$CO_2/(CO_2+CO)$		-5674	-1877	250	126	-0.98	-0.95	<0.001	<0.001

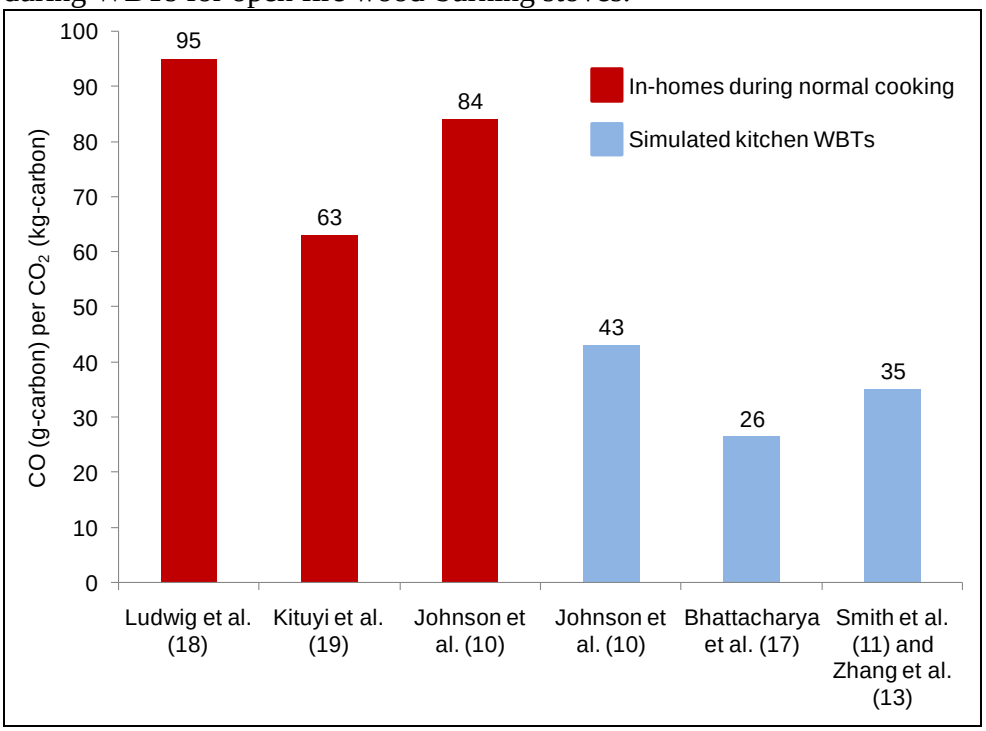
Model predictions had r^2 values ranging from 0.91-0.98 for the full GHG set, but were slightly lower (0.65-0.98) for the more restricted Kyoto gases and renewable harvesting. The largest increase in uncertainty occurs for 0% fNRB under the Kyoto set, when the renewable open fire emission factor, which has a relatively low r^2 value of 0.65, contributes 46% of the uncertainty in CO_2-e savings (see Figure 1). Uncertainty introduced by these models resulted in a 1% and 4% increase in 95% confidence intervals of CO_2-e savings, using the full and Kyoto GHG set, respectively. Since the relationship between the $CO_2/(CO_2+CO)$ 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 $CO_2/(CO_2+CO)$ ratio to estimate emissions requires calibration in local community settings. Thus this approach is perhaps better suited as an inexpensive verification tool for CO_2-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:

$$fNRB_v = \left| \frac{FWS_v - C_1}{C_1} \right| \qquad (S5)$$

Where $fNRB_v$ 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:

$$FWS_v = \sum_{j=1}^{8} (A_{vj} * P_j) \qquad (S6)$$

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.

$$P_j = \frac{B_j * 2 * Ff_j}{t_j} \qquad (S7)$$

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*2/t_j correspond to the mean annual increment (MAI) by land cover class.

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

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

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:

$$C_l = \left(U_l * FC\right) + \left(M_l * FCM\right) \qquad \text{(S8)}$$

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.

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