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EVALUACIÓN DE $PM_{2.5}$, CO Y PAHs COMO INDICADORES DE CONTAMINACIÓN INTRAMUROS POR COMBUSTIÓN DE LEÑA: SU RELACIÓN CON FACTORES DE EXPOSICIÓN

T E S I S

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CYNTHIA ARMENDÁRIZ ARNEZ

DIRECTOR DE TESIS: DR. OMAR R. MASERA CERUTTI

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Dr. Isidro Ávila Martínez
Director General de Administración Escolar, UNAM
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Por medio de la presente me permito informar a usted que en la reunión ordinaria del Comité Académico del Posgrado en Ciencias Biológicas, celebrada el día 23 de agosto del 2010, se acordó poner a su consideración el siguiente jurado para el examen de DOCTORA EN CIENCIAS de la alumna **ARMENDÁRIZ ARNEZ CYNTHIA** con número de cuenta **95620329,** con la tesis titulada: **"Evaluación de $PM_{2.5}$, CO y PAHs como indicadores de contaminación intramuros por combustión de leña: su relación con factores de exposición"**, bajo la dirección del **Dr. Omar Raúl Masera Cerutti.**

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Coordinador del Programa

c.c.p. Expediente del interesado

Edif. de Posgrado P. B. (Costado Sur de la Torre II de Humanidades) Ciudad Universitaria C.P. 04510 México, D.F.
Tel. 5623-0173 Fax: 5623-0172 http://pcbiol.posgrado.unam.mx

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RESUMEN

La contaminación intramuros como resultado de la combustión de biomasa en fogones abiertos se ha reconocido como uno de los principales contribuyentes a la carga mundial de enfermedades. La combustión de leña en condiciones de poca ventilación y estufas ineficientes conduce a niveles extremadamente altos de partículas respirables, gases y otros compuestos tóxicos. La exposición a estos compuestos se ha asociado recurrentemente con efectos perjudiciales a la salud, sobre todo de mujeres que pasan alrededor de 4 a 6 horas en la cocina. En este estudio, se evaluó el impacto de la estufa Patsari en la reducción de las concentraciones intramuros y de exposición personal de partículas ($PM_{2.5}$), monóxido de carbono (CO) e hidrocarburos aromáticos policíclicos (PAHs) en 60 casas en dos comunidades de la meseta Purhépecha en Michoacán, México. Se encontraron concentraciones 24-h $PM_{2.5}$ promedio de exposición personal de 0.29 mg/m^3 y concentraciones 48-h $PM_{2.5}$ promedio en la cocina de 1.269 mg/m^3 así como una concentración 24-h total de PAHs de 2,293 ng/m^3. Si estas concentraciones son los niveles cotidianos de la gente rural en México, una gran proporción de la población nacional está crónicamente expuesta a concentraciones de contaminantes que exceden hasta en 20 veces los niveles máximos permitidos por el gobierno mexicano cuya exposición causa efectos adversos en la salud. La instalación y uso de estufas Patsari redujo en 74% la estimación de exposición personal. Así mismo, se obtuvieron reducciones de 77% en la cocina y 78% en la exposición personal respecto a CO. La relación entre las reducciones en la cocina y las reducciones en exposición personal cambiaron en función del contaminante, el tipo de estufa y la categoría de adopción. En la combustión de leña en fogones abiertos, la emisión y contaminación por partículas se ha asociado claramente con efectos en la salud y las concentraciones intramuros se han utilizado ampliamente como aproximaciones de exposición personal en numerosos estudios publicados. Se asume que la distribución de los tamaños de partícula para el fogón y la Patsari son iguales y que la relación entre las concentraciones intramuros y las de exposición personal también. Para medir el impacto de estas suposiciones, se midió la distribución de los tamaños de partícula en casas usuarias de fogón y Patsari. La concentración de PM <0.25 µm se redujo en 72% en las viviendas con estufa Patsari; esto representa una disminución en la contribución de este tamaño de partículas a la concentración de masa total de $PM_{2.5}$ del 68% al 48%. Como resultado el diámetro mediano de masa (MMD) aumentó 29% en las casas usuarias de Patsari. Las concentraciones de $PM_{2.5}$ de exposición personal para casas usuarias del fogón tradicional representaron el 61% de las concentraciones de la cocina. Por otro lado las concentraciones de $PM_{2.5}$ de exposición personal para usuarias de estufas Patsari representaron el 77% de la concentración de la cocina. Se concluye que si no se toman en cuenta los cambios en las propiedades físicas y la composición de los contaminantes asociados a la introducción de

estufas eficientes, se puede incurrir en una subestimación de los beneficios potenciales a la salud.

ABSTRACT

Indoor air pollution resulting from biomass burning in rural households in open fires is now recognized as a major contributor to the global burden of disease. Combustion of wood fuel in poorly ventilated kitchens and inefficient stoves leads to extremely high concentrations of respirable particulates, gases and toxic compounds. Exposure to these pollutants has been clearly linked with adverse heatlh effects, especially in women who spend 4 to 6 hours in the kitchen. The impact of an improved wood burning stove (Patsari) in reducing personal exposures and indoor concentrations of particulate matter ($PM_{2.5}$), carbón monoxide (CO) and polycyclic aromatic hydrocarbons (PAHs) was evaluated in 60 homes in 2 rural communities of Michacan, Mexico. Average $PM_{2.5}$ 24h personal exposure was 0.29 mg/m^3 and mean 48h kitchen concentration was 1,269 mg/m^3 for women users of traditional fogon. An indoor PAH total concentration of 2,293 ng/m^3 was found for fogon homes. If these concentrations are typical of rural conditions in Mexico, a large fraction of the population is chronically exposed to levels of pollution far higher than ambient concentrations found by the Mexican government to be harmful to human health. Installation of Patsari stoves resulted in 74% reduction in median 24h $PM_{2.5}$ personal exposures. Corresponding reductions in CO were 77% and 78% for median 48-h median kitchen concentrations and median 24-h personal exposures, respectively. The relationship between reductions in kitchen concentrations and reductions in median personal exposure changed for the different pollutants, stove type and adoption category. Particulate pollution has been clearly linked with adverse health impacts from open fire cookstoves and indoor air concentrations are frequently used as a proxy for exposures in health studies. Implicit are the assumptions that the size distributions for the open fire and improved stove are not significantly different, and that the relationship between indoor concentration and personal exposure is the same between stoves. To evaluate the impact of these assumptions size distributions of particulate matter in indoor air were measured in homes with fogon and Patsari stove. On average indoor concentrations of particles less than 0.25 µm were 72% reduced in homes with improved Patsari cookstoves reflecting a reduced contribution of these size fraction to $PM_{2.5}$ mass concentrations from 68% to 48%. As a result the mass median diameter of indoor $PM_{2.5}$ particulate matter increased by 29% with the Patsari stove compared to the fogon. Personal $PM_{2.5}$ exposure concentrations for fogón homes were approximately 61% of kitchen concentrations levels. In contrast personal exposure concentrations were 77% times kitchen concentrations for Patsari users. Thus if indoor air concentrations are used in health and epidemiologic studies significant errors may result if the shift in size distribution and the change in relationship between indoor air concentrations and personal exposure concentrations are not accounted for between different stove types.

CAPÍTULO 1

1.1 Introducción

El 11% de la energía total que se consume en el mundo se obtiene a partir de biomasa. Para algunos países en vías de desarrollo, como en la India o Sudáfrica, la biomasa representa el 90% de su fuente energética. Así mismo, aproximadamente 3,000 millones de personas dependen de la biomasa para usos domésticos (Ezzati & Kammen, 2002). En México, 25 millones de personas utilizan la leña para cocinar o calentar sus viviendas (Masera et al, 2005) La presión sobre el acceso a la leña ha aumentado en las últimas décadas y, aunque la leña no es la principal causa de deforestación (Filmer y Pritchett 2002, Masera et al 2000), su escasez contribuye a aumentar el estrés ambiental y el agotamiento forestal (Von Schirnding et al, 2002).

La leña se utiliza principalmente en fogones abiertos al interior de las viviendas donde se liberan altas cantidades de contaminantes. De hecho, la combustión incompleta de biomasa produce una mezcla de gases (CO, NO_x, SO_x) y partículas (asociadas a compuestos orgánicos o inorgánicos), cuya exposición tiene repercusiones importantes a la salud (Avakian, 2002; Smith, 2004). Los niveles de contaminantes encontrados al interior de las viviendas rurales dependen de varios factores como: calidad y tipo de combustible, características de la vivienda, prácticas de cocinado, ventilación y estación del año (Saksena et al, 1992). La Contaminación Intramuros (CI) es un fenómeno muy complejo, pues pueden haber diferencias en los niveles de contaminantes entre familias, entre las estaciones del año, entre los días de la semana (He et al, 2005) e incluso a lo largo del día (Ezzati et al 2000). Algunos estudios reportan concentraciones 10 a 50 veces más altas de CI comparadas con estudios en ambientes urbanos exteriores (Von Schirndig et al, 2002). La EPA (Environmental Protection Agency de los EUA), ha establecido niveles permitidos de $PM_{2.5}$ de 65 $\mu g/m^3$ pero en países de África, la India y América este contaminante alcanza valores de 300 a 3,000 $\mu g/m^3$ e incluso puede llegar hasta 30,000 $\mu g/m^3$ durante la preparación de alimentos (Bruce et al., 2000).

Las emisiones obtenidas de la combustión de leña dependen fundamentalmente de su composición química y las condiciones del proceso de combustión. La madera está constituida principalmente de dos polímeros estructurales: 65% de celulosa y hemicelulosa, 25% de lignina y 10% de elementos no estructurales como metabolitos secundarios que incluyen a los terpenos, terpenoides, fenoles y algunos minerales. La celulosa es un polímero lineal formado por la unión de moléculas de glucosa y es el principal componente de la pared celular del tejido vegetal. Las ligninas son fracciones extremadamente complejas y difíciles de caracterizar. Constituyen un polímero aromático, heterogéneo, ramificado, donde no existe ninguna unidad repetida definidamente (Tissari, 2008). Durante el proceso de combustión de la leña, los componentes se deshidratan, oxidan, pirolizan y se transforman en compuestos orgánicos que pueden volatilizarse y asociarse a partículas o quedarse en la fase gaseosa y reaccionar para formar otros compuestos (Naeher et al, 2007, Tissari, 2008). Este proceso da lugar a un espectro diverso de contaminantes cuya formación, distribución y caracterización es motivo de intensa investigación. La proporción y el tipo de contaminantes generados por combustión puede variar en función de la especie utilizada; de esta forma la combustión de pino produce emisiones ricas en derivados de la lignina como o el guayacil y la de encinos en derivados del siringol (Rogge et al, 1998).

Las partículas se han utilizado ampliamente como indicadores de la calidad ambiental. Rogge et al (1998) estimaron que se liberan 6.2 g de partículas finas (PF) /Kg encino quemado y 13 g PF/ Kg de madera suave y que la combustión residencial de leña contribuye en un 14% al promedio anual de emisiones de carbono orgánico en la atmósfera urbana de Los Angeles. Durante mucho tiempo se pensó que era la masa de las partículas lo que determinaba su efecto en la salud; sin embargo estudios recientes (See & Balasubramanian, 2006; Mitra et al, 2002; Naeher et al, 2007) han encontrado que otras propiedades físicas como el número, la superficie, el tamaño y la composición química tienen una estrecha correlación con el efecto que producen en el organismo de los seres vivos. Compuestos como los hidrocarburos policíclicos aromáticos (PAH's), algunos de ellos clasificados por la EPA como geno-tóxicos y cancerígenos, se producen por la combustión incompleta de biomasa y se encuentran en fase gaseosa y asociados a partículas de diferentes tamaños; éstos compuestos constituyen una de las fracciones más tóxicas del espectro de compuestos que forman el humo (Chen et al, 2004).

La exposición continua a los sub-productos de la combustión tiene repercusiones a la salud; la contaminación intramuros (CI) se ha relacionado recurrentemente con Infecciones respiratorias agudas (IRA), Enfermedad Pulmonar Obstructiva Crónica (EPOC), cáncer de pulmón, cataratas, tuberculosis, ataques de asma, bajo peso al nacer y enfermedades cardiovasculares. (Ezzati et al, 2001, Albalak et al, 1999, Balakrishnan et al, 2002). Además, es causa de 1.6 millones de muertes al año y 38.5 millones de años-vida perdidos por discapacidad ajustada (DALY's) o el 3% de la mortalidad a nivel mundial. Hay evidencias de 13 estudios realizados en países en vías de desarrollo de que los niños que viven en casas que usan combustibles sólidos tienen entre 2 y 3 veces mayor riesgo de padecer enfermedades respiratorias agudas que los niños no expuestos (Smith et al., 2000b). Los efectos a la salud se dan por diversos mecanismos que incluyen: inhalación continua de gases o partículas de diferentes tamaños asociadas a compuestos tóxicos que causan desde irritación de los tejidos hasta daño en el DNA (Naeher et al., 2007).

En México, se han detectado concentraciones elevadas de partículas en ambientes interiores (Brauer et al, 1996, Saatkamp et al., 2000, Riojas-Rodríguez et al, 2000). Se reportaron concentraciones máximas de 1,049 $\mu g/m^3$ y 7,705 $\mu g/m^3$ durante 16 h de monitoreo, cerca de la estufa en estaciones de secas y lluvias respectivamente (Riojas-Rodríguez, 2001) y un promedio de 655 a 995 $\mu g/m^3$, durante actividades de cocinado (Saatkamp et al, 2000). Aunque las concentraciones medidas en México son menores que las detectadas en países como Africa o India, son hasta 10 veces más grandes que los valores reportados en estudios de ambientes urbanos. Se ha estimado que el índice de mortalidad puede aumentar hasta un 10% por cada 100 $\mu g/m^3$ de aumento en la concentración de PM_{10} (Brauer et al, 1996).

La estufa comúnmente utilizada en las áreas rurales para la cocción es el fogón. La estructura básica del fogón rural tradicional consiste en tres piedras apoyadas en el suelo o en una estructura en forma de herradura o “U” hecha de barro, cemento o ladrillo donde se coloca un comal de barro o metal en la parte superior; puede ser alimentado desde diferentes puntos y las emisiones generadas durante el proceso de combustión se distribuyen libremente al interior de la cocina.

Existen diferentes estrategias para mitigar los efectos de la CI. Se clasifican de acuerdo a si modifican: i) la fuente contaminante (combustible), ii) el ambiente doméstico (tipo de estufa) - donde se inserta este proyecto - o iii) el comportamiento de las usuarias.

Las estufas eficientes (EE) son una alternativa tecnológica desarrollada para disminuir el consumo de leña, reducir la CI y disminuir el impacto de los contaminantes en la salud de las usuarias. La EE considerada para este proyecto es la Patsari, que en Purhépecha significa “la que guarda”; se define como un dispositivo de cocción cuyas características principales son que posee una cámara de combustión cerrada y se alimenta desde un solo punto, (Berrueta, 2007). Está hecha de ladrillo y cemento y ha sido mejorado con un sistema interno de túneles y espacios con ángulos de construcción específicos y materiales aislantes que promueven la conducción de las emisiones hacia el exterior de la vivienda a través de una chimenea y mejoran la eficiencia de combustión. De acuerdo a los protocolos internacionales de eficiencia energética mejora la distribución del calor y promueve el ahorro de leña (Berrueta, 2007).

1.2 Planteamiento del problema

Son pocos los estudios realizados en materia de CI por combustión de leña en comunidades rurales y todavía menos los que se refieren a la mitigación (reducción) de emisiones por la adopción de tecnologías alternativas más limpias. Se desconoce cómo se comportan los contaminantes emitidos y sus variaciones en el tiempo. La relación de contaminación intramuros con efectos a la salud por exposición al humo es motivo de intensa investigación actual ya que se desconocen el mecanismo y las dosis por las cuales se dan las enfermedades. Por ejemplo Smith et al (2000b) estimaron que las Infecciones Respiratorias Agudas son la principal causa de muerte infantil (4.1 millones al año) en los países menos desarrollados;

en referencia a la exposición intramuros (por uso de combustibles sólidos), las concentraciones tan altas de contaminantes y el tiempo que pasan los niños con sus madres expuestos en las labores de cocinado aumentan el riesgo de padecimientos respiratorios. Debido a la magnitud de la población que está en riesgo, es urgente desarrollar estudios que aumenten la confiabilidad de la relación causa-efecto, que cuantifiquen el riesgo a enfermedades con mayor precisión y determinen la efectividad en las reducciones de contaminantes y en la exposición.

Aunque en la última década la evidencia sobre morbilidad y mortalidad mundial por uso de combustibles sólidos (Smith et al 2004), han impulsado la asignación de recursos a la investigación de CI, todavía se desconocen los niveles de contaminantes a los que están expuestas diariamente mujeres usuarias de fogones abiertos así como los efectos que dichas emisiones resultado de la combustión, en conjunto, pudieran tener en la salud (Naeher et al. 2007). Aún menos estudiado es el impacto de las estufas eficientes como una medida para mitigar la contaminación intramuros.

La investigación sobre las reducciones de las concentraciones ambientales de compuestos por el uso de estufas eficientes se ha centrado en la masa de los contaminantes sin tomar en cuenta otras propiedades físicas como número, tamaño y/o su composición química. Uno de los compuestos de mayor riesgo para la salud son los hidrocarburos aromáticos policíclicos (PAHs) asociados a las partículas (Ballard-Tremeer & Jawurek 1996, Smith, 1987). Aunque hay estudios donde se afirma que los PAHs son una fracción significativa de las partículas por combustión de leña (Oahn et al, 1999, Fine et al 2002) la cantidad de factores que afectan la tasa de emisiones durante la combustión, como el tipo de combustible, la ventilación, el tipo de estufa, las condiciones de la vivienda, etc. (Chen Y., 2004) dificultan los estudios de caracterización. Los PAHs juegan un papel importante como precursores del proceso fotoquímico de la generación de ozono (Mitra et al, 2002). Así mismo, algunos terpenos y compuestos orgánicos volátiles pueden reaccionar con el ozono para incrementar el número de partículas en el ambiente o formar compuestos como el formaldehído cuya exposición tiene efectos nocivos a la salud (Fan et al, 2003). Finalmente, varios estudios epidemiológicos relacionan directamente la exposición de PAHs con enfermedades como cáncer (Armstrong et al., 2004) y la NIOSH (Nacional Institute of Ocuppational Safety and Health), la IARC (International Agency for Research on Cancer) y la EPA (Environmental Protection Agency) han publicado listas de los PAHs considerados como cancerígenos probables y posibles (CDC Report, 2005).

Tener una caracterización física y química detallada de las emisiones de partículas por la combustión residencial de leña es entonces clave para entender su contribución a la contaminación de interiores, a la exposición de las usuarias y sus repercusiones a la salud (Smith, 2002). En el caso específico de México, se han hecho evaluaciones puntuales de los niveles de CI en Michoacán (Saatkamp et al., 2000) y Chiapas

(Riojas-Rodríguez, 2001) donde se encontraron picos máximos de exposición de hasta 3,000 $\mu g/m^3$ al interior de las cocinas y concentraciones que exceden por mucho los límites máximos permitidos por las normas internacionales. Sin embargoaún no se han repondido preguntas como: ¿cuáles son los niveles reales de contaminación a los que están expuestas las usuarias de leña?, ¿son las EE una alternativa efectiva en la mitigación de la CI? Y finalmente, ¿cuáles son los cambios en la composición de los sub-productos de la combustión por el uso de EE?

1.3 Hipótesis General

El uso de EE es una alternativa para mitigar el efecto de la contaminación intramuros porque disminuye las concentraciones de contaminantes hacia el interior de la vivienda y cambia la composición de los productos de combustión.

1.3.1 Hipótesis Específicas

- Los niveles intramuros de $PM_{2.5}$ y CO así como la exposición personal a estos contaminantes por el uso de fogones abiertos sobrepasan los niveles máximos permitidos según la NOM-025-SSA1-1993.

- El uso de estufas eficientes disminuye significativamente las concentraciones micro-ambientales de contaminantes y la exposición personal.

- La reducción de $PM_{2.5}$ al interior de las cocinas será significativa en usuarias que han adoptado la estufa adecuadamente.

- El uso de estufas eficientes modifica la composición de los contaminantes y subproductos de la combustión (PM y PAH's).

1.4 Preguntas de investigación

Con base en la revisión documental de los factores que determinan las concentraciones de contaminantes intramuros, se plantearon las siguientes preguntas:

1. ¿Cuáles son los niveles intramuros y de exposición diarios a $PM_{2.5}$ y CO a los que están sujetas las mujeres cuando usan fogones abiertos o Patsaris?

2. ¿Cuáles son los niveles de reducción en las concentraciones de partículas y monóxido de carbono al interior de las cocinas por el uso de Patsaris?

3. ¿Cuál es la relación que existe entre la concentración promedio de $PM_{2.5}$ y monóxido de carbono dentro de las cocinas donde se usan Patsaris?

4. ¿Cuál es la relación entre las concentraciones de exposición personal y las concentraciones de la cocina?

5. ¿Existen diferencias en la distribución del tamaño de las partículas en función del tipo de estufa utilizada (fogón vs EE)?

6. ¿Son significativas las concentraciones microambientales y de exposición personal de PAH's en función del tipo de estufa utilizada?

7. ¿Cuál es la relación entre la exposición personal y las concentraciones intramuros de PAHs?

1.5 Objetivo general

A partir de las preguntas de investigación, el objetivo general fue Analizar los niveles de $PM_{2.5}$, CO y PAHs dentro de las viviendas generadas por la combustión de leña en hogares rurales usando sus tecnologías locales tradicionales (fogón abierto) y documentar su reducción al adoptar la estufa Patsari.

1.5.1. Objetivos particulares

Como objetivos particulares se plantearon:

- Medir las concentraciones de CO y $PM_{2.5}$ al interior de hogares con fogones abiertos y EE.
- Analizar posibles correlaciones entre las concentraciones de los diferentes contaminantes dentro de las cocinas ($PM_{2.5}$-CO).
- Establecer los niveles de exposición personal de las mujeres en el ambiente rural con el uso de monitores continuos y diarios tiempo-actividad.
- Medir la concentración de $PM_{2.5}$ en la estufa
- Obtener la distribución de partículas en función del tamaño.
- Analizar los niveles de PAHs en la cocina y en la exposición personal.

1.6 Organización de la tesis

Este trabajo está organizado en 4 capítulos y varios anexos en los que se presentan los instrumentos de análisis y algunas publicaciones relacionadas con contaminación intramuros.

En el primer capítulo se hace una introducción al tema de contaminación intramuros por combustión de leña, se plantea el problema y las preguntas de investigación, las hipótesis, los objetivos y el contenido de la tesis.

En el segundo capítulo se presenta el marco teórico de esta investigación.

En el tercer capítulo se presentan los resultados derivados de esta investigación agrupados en cuatro artículos; en el primer artículo publicado (apartado 3.1) se presentan los antecedentes de la investigación y datos generales del proyecto de implementación de EE.

El segundo artículo publicado (apartado 3.2) presenta los niveles de las concentraciones de $PM_{2.5}$ y CO asociadas a la instalación de estufas Patsari. Se reportan las reducciones encontradas y los niveles de exposición personal.

El tercer artículo publicado (apartado 3.3) presenta la distribución en los tamaños de partícula asociados con la implementación y uso de EE Patsari.

El cuarto artículo (en revisión) presenta los resultados del análisis de las concentraciones de PAHs por combustión de leña en fogones y estufas Patsari.

Finalmente en el cuarto capítulo se revisan los principales hallazgos de esta investigación, se discuten sus posibles aplicaciones para futuros proyectos de difusión de estufas eficientes, se dan conclusiones y recomendaciones derivadas de la investigación.

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CAPÍTULO 2
MARCO TEÓRICO

2.1 LA LEÑA COMO COMBUSTIBLE

La leña es un combustible de origen vegetal. Las propiedades de la leña afectan significativamente las condiciones de combustión. A diferencia de otros combustibles, la leña contiene cerca del 80% de compuestos volátiles y está constituida por 47-52% de carbono (C), 38-45% de oxígeno (O) y 6.1-6.3% de hidrógeno (H) (Van Loo & Koppejan, 2008).

Estructuralmente la leña está compuesta de celulosa (40-45%), hemicelulosa (20-35%), lignina (15-30%) y compuestos extraíbles. Las paredes fibrosas de la madera contienen fundamentalmente celulosa ($C_6H_{10}O_5$) que es un polímero de glucosa. La hemicelulosa ($C_5H_8O_4$) consiste de varias unidades de azúcares como la glucosa que rodean las fibras de celulosa. La lignina ($C_{40}H_{44}O_{14}$) es un polímero complejo de alto peso molecular que da estructura y soporte a la parte fibrosa de la madera (Tissari, 2008).

La madera también contiene compuestos inorgánicos ligados a la estructura orgánica en las siguientes proporciones: nitrógeno (menor al 0.5%), minerales (menor al 0.5%) siendo los más abundantes el calcio, potasio, magnesio, manganeso, azufre, cloro, fósforo, hierro, aluminio y zinc. Finalmente la leña tien un contenido de agua muy variable que va desde el 6% en tablones de madera secada hasta el 60% en madera fresca (Tissari, 2008).

2.2 EL PROCESO DE COMBUSTIÓN

La combustión es un proceso exotérmico irreversible donde el oxígeno reacciona con la madera y este fenómeno químico libera energía y calor. Esto es importante desde el punto de vista de esta investigación porque se emiten diferentes compuestos en función de la temperatura; la cantidad de oxígeno disponible y el tiempo de permanencia de los compuestos generados bajo las condiciones antes mencionadas (Smith, 1987). Se han identificado varias etapas en el proceso de combustión: i) evaporación de agua y calentamiento del combustible, ii) pirolisis, iii) fase de “flama” donde se producen reacciones en fase gaseosa y iv) la quema de carbón. La mayoría de las veces las cuatro etapas ocurren simultáneamente en diferentes partes del combustible que se está consumiendo. En la Fig. 1 se pueden observar las temperaturas en las que ocurre cada una de las etapas descritas.

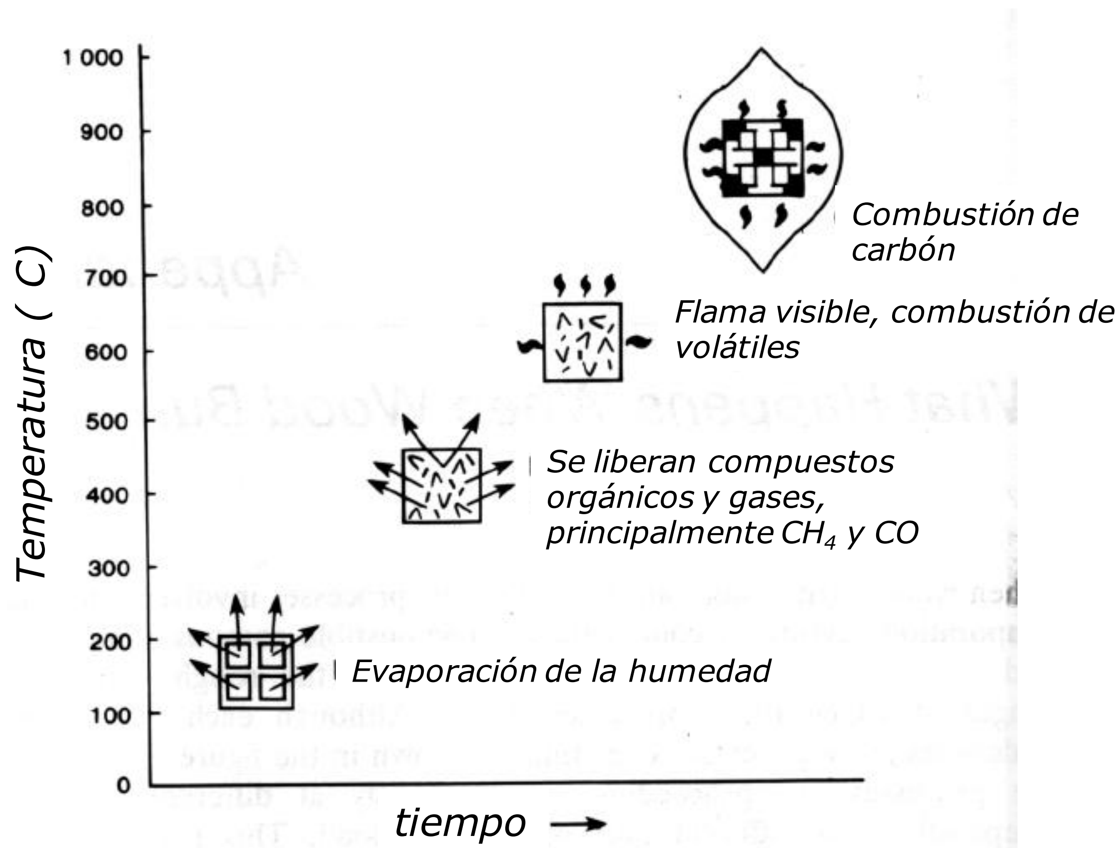

Fig. 1. Las cuatro etapas principales del proceso de combustión y los rangos de temperatura en las que se llevan a cabo. Fuente: Smith, K.R. (1987). Biofuels, air pollution and health. A global review . Plenum Press, New York, USA.

Las primeras dos etapas necesitan calor para llevarse a cabo mientras que la etapa de “flama”y la quema de carbón liberan energía y calor. En la combustión de leña, las reacciones tienen lugar básicamente entre los compuestos gaseosos emitidos, sin embargo durante la quema de carbón, las reacciones primordiales son entre los compuestos gaseosos y el carbono en la superficie del combustible sólido remanente.

En la etapa de evaporación de la humedad, la temperatura se incrementa hasta 100°C. Mientras la madera se calienta, el agua se traslada desde las capas más profundas a la superficie hasta alcanzar la temperatura de evaporación. Este proceso necesita calor por lo que la temperatura ganada por el combustible desciende. Aumenta la capa de vapor alrededor del combustible y por lo tanto su grosor y disminuye el calor transmitido por convección por lo que la madera arde lentamente hasta que ya no queda agua que evaporar. Esto dependerá de las características intrínsecas del combustible. Además del contenido natural de agua presente en la leña, el oxígeno e hidrógeno liberados por la combustión forman moléculas de agua y alrededor de un 6% (1.32 MJ/kg) de la energía química de la leña (20 MJ/kg) es necesaria para evaporar el agua formada en la combustión (Smith 1987, Van Loo & Koppejan, 2008).

Durante la pirolisis, los constituyentes del combustible se hidrolizan, oxidan, deshidratan y se degradan las estructuras complejas de los polímeros. Muchos de los sub-productos líquidos y gaseosos como los compuestos orgánicos volátiles, el agua, CO_2, H_2 y CO se forman en esta fase (Smith, 1987; Rogge et al., 1998). Hay dos tipos de pirolisis:

- La pirolisis endotérmica o de baja temperatura. Ocurre de 100 a 280°C. Las moléculas de la leña empiezan a descomponerse formando H_2, H_2O, CH_4, CO_2, CH_3COOH, CO y ácido fórmico.

- La pirolisis exotérmica. Ocurre de 280 a 600°C. La descomposición de hemicelulosa se da entre los 200-350°C y la celulosa de 250-450°C. A 400°C se han producido la mayoría de los volátiles (según Sheinbaum, se han encontrado alrededor de 213 compuestos); la lignina se descompone entre los 200-500°C pero la descomposición completa ocurre a temperaturas mayores (Tissari, 2008, Smith, 1987).

En la etapa de "flama" la temperatura es de 600 a 800°C; los volátiles emitidos se mezclan con el oxígeno disponible y arden produciendo una flama visible. Si no hay suficiente oxígeno o hay poca turbulencia que impida la mezcla de gases o si no hay suficiente tiempo de residencia de los compuestos producidos a las temperaturas adecuadas, las especies emitidas se escapan en su forma original o en alguna de sus formas parcialmente oxidadas (Smith, 1987, Tissari, 2008).

En la etapa de quema de carbón, el rango de temperatura es de 800 a 1,000°C y cuando los componentes de la leña se han pirolizado por completo, se produce el carbón que arde incandescente con una temperatura de 800°C. El carbón es un mal conductor de calor y su formación durante la pirolisis retarda la transferencia de calor al interior del combustible. Un aumento del flujo de aire durante esta etapa aumenta la velocidad de reacción y por lo tanto incrementa el oxígeno disponible en la superficie del combustible sólido (Smith, 1987).

2.3 EFECTOS A LA SALUD ASOCIADOS CON EL USO DE LEÑA

La ruta en la cual se lleva a cabo la asimilación de contaminantes por el organismo cuando está expuesto a una fuente potencial de contaminación (Fig. 2) es: i) Las emisiones de contaminantes dependen del tipo de combustible a quemar, la cantidad y de qué manera se realiza la combustión, ii) La concentración de contaminantes en el aire depende la las emisiones pero también de las condiciones atmosféricas (o niveles de ventilación del lugar donde se lleva a cabo la contaminación de interiores), iii) La exposición depende de qué cantidad de contaminantes se respiran y durante cuánto tiempo, iv) La dosis mide la cantidad de contaminantes depositados en el organismo y depende no solamente de la exposición sino de varios factores en el intervalo de respiración y el tamaño de partículas a medir, v) Los efectos en la salud dependen no solamente de la dosis sino también de características del individuo como la edad, sexo, si fuma o no y la presencia de otras enfermedades (Smith, 1987).

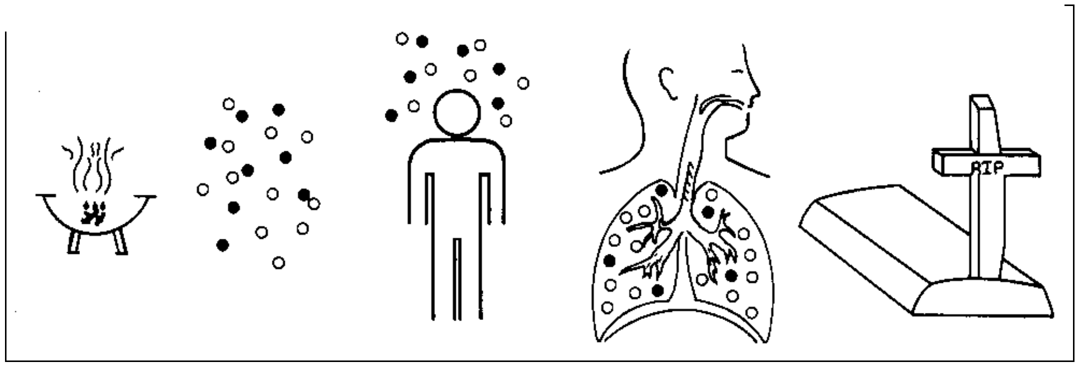

Fig. 2. Puntos principales del proceso de combustión donde puede ser descrita, medida y controlada la contaminación de interiores. Fuente: Smith, 1987. Biofuels, air pollution and health. A global review . Plenum Press, New York, USA.

La exposición a los sub-productos de combustión es causa importante de morbilidad y mortandad en los países en desarrollo (Fig. 3)(Ezzati & Kammen, 2002). Se han estudiado las asociaciones entre exposición a combustibles sólidos e infecciones respiratorias agudas, cáncer de pulmón, enfermedades pulmonares obstructivas crónicas, cataratas, tuberculosis, ataques de asma, problemas en mujeres embarazadas y enfermedades cardiovasculares (Lan et al., 2002; Boy et al, 2002; Bruce et al, 2000; Ezzati & Kammen, 2001; Mishra et al, 2004; Smith et al, 2004; Smith et al, 2000). La variedad en la dependencia de combustibles sólidos y los programas de intervención en el mundo es enorme, igual es la cantidad de muertes producidas por exposición al humo contaminante resultado del proceso de combustión. El mayor número de muertes prematuras está en el sureste de Asia y en África (Fig. 3).

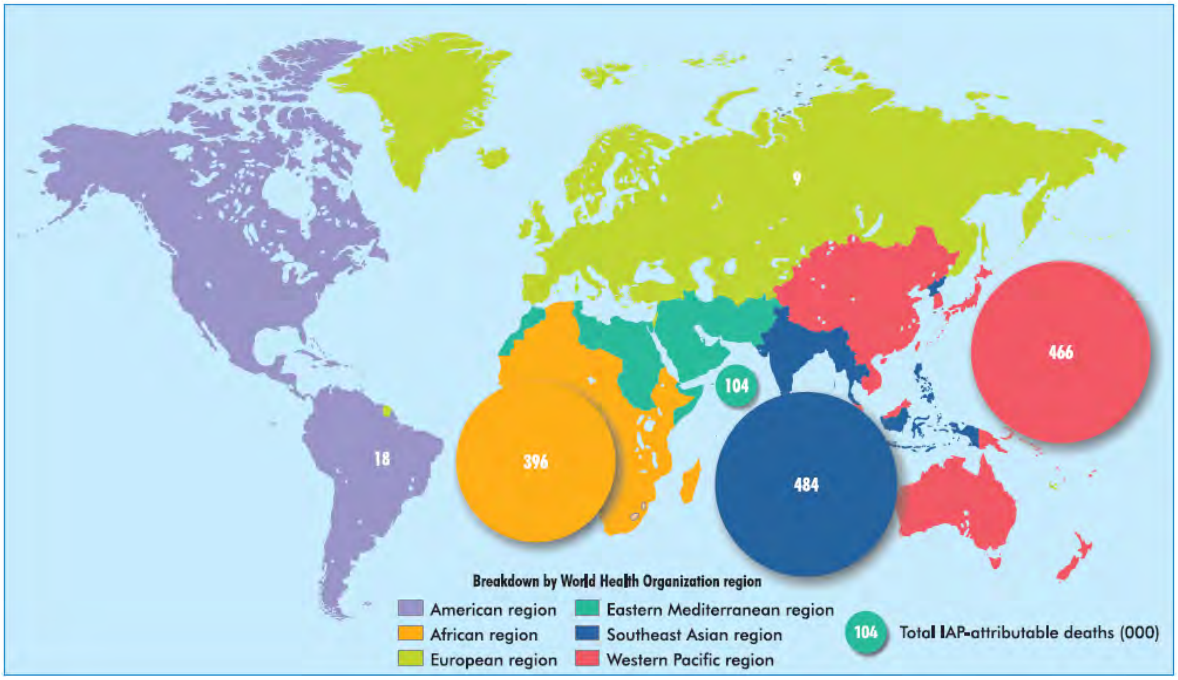

Fig. 3. Muertes por año causadas por exposición a contaminantes intramuros, OMS. Nota: Los países se agrupan de acuerdo a las regiones de la OMS, las muertes incluyen, principalmente en China, aquellas atribuibles al uso de carbón mineral. Fuente: World Health Organization, 2006.

Combinando las probabilidades de riesgo con los patrones de exposición, se piensa que la contaminación de interiores es causa del 4% del total de enfermedades a nivel mundial y excede un billón de muertes prematuras al año; esto quiere decir que se encuentra en niveles mayores a los dos principales factores de riesgo de la población que son la desnutrición (16%) y la escasa sanidad del agua (7%). En 1990 se reportó un número más alto de muertes en comparación con drogas, hipertensión, contaminación exterior, riesgos ocupacionales, alcohol, guerra, accidentes vehiculares, homicidio y estuvo a la par con tabaco y sexo sin precaución (Naeher et al, 2007).

Los programas de implementación de estufas eficientes de leña contribuyen a disminuir los efectos por exposición al humo de leña (Naeher et al., 2007, Romieu et al, 2008). En la Fig. 4 se presentan los porcentajes de reducción encontrados en varios países del mundo por la introducción de diferentes tipos de estufas:

Reference	Stoves studied	Results
Ballard-Tremeer & Jawurek (1996)	Laboratory test: Open fire Open fire with grate One-pot metal stove (no flue) Two-pot ceramic stove (no flue) Two-pot metal stove (with flue)	Average smoke emissions lowest for fire on grate and 2-pot ceramic stove; others higher by factor of 1.5–3. CO and SO_2 higher from 3 stoves than 2 fires; stoves higher by factor of 2-3 (CO) and 3–10 (SO_2).
Ezzati *et al* (2000a)	Field test (Kenya): Open fire 3 improved wood stoves (no flue) 3 improved charcoal stoves (no flue)	- Improved wood stove reduced TSP by 48% (1822 $\mu g/m^3$) (burning) and 77% (1034 $\mu g/m^3$) (smouldering). - Improved charcoal stove reduced TSP by 63-65% (559-578 $\mu g/m^3$) during burning. - Transition from wood to charcoal reduces TSP by 87% (3035 $\mu g/m^3$) (burning); 92% (1121 $\mu g/m^3$) (smouldering).
Joshi *et al* (1989)	Simulated field test (India): 1 traditional stove (no flue) 3 improved stoves (no flue) wood (w) crop residue (c) dung (d)	- Both TSP and CO emissions were higher from the 2 more efficient improved stoves: - Traditional stoves (mean - g/kg of fuel): TSP = 1.9 (w); 2.7 (c); 52.5 (d) CO = 17.0 (w); 26.0 (c); 42.0 (d) - Improved stoves (mean - g/kg of fuel): TSP = 2.4 (w); 9.4 (c); n/a (d) CO = 47.5 (w); 91.0 (c); n/a (d)
Joshi *et al* (1991)	Simulated field test (India): 2 heavy stoves with flues – 'thapoli' (bricks and clay) 'sahyog' (clay) wood (w) crop residue (c) dung (d)	- Flue can remove 80% CO and 60% TSP from indoors. - Chimeys emitting emissions indoors lead to higher CO than stoves without chimneys. - TSP rose by up to 1100% with dung. - Sahyog vented outside [4m flue] - g/kg of fuel: TSP = 0.5 (w); CO = 5.0 g/kg (w) Sahyog vented inside [1.8 m flue] - g/kg of fuel: TSP = 1.3 (w); CO = 25.0 g/kg (w)
McCracken & Smith (1998)	Field test (Guatemala): open fire *plancha* stove water boiling test (W) standard cooking test (C)	Plancha reduced $PM_{2.5}$ by 87-99% and CO by 91-96% for water-boiling and cooking tests respectively. Open fire: $PM_{2.5}$ = 14,800 $\mu g/m^3$ (W); 27,200 (C) CO = 86,400 $\mu g/m^3$ (W); 118,000 (C) *Plancha:* $PM_{2.5}$ = 1,170 $\mu g/m^3$ (W); 450 (C) CO = 2,040 $\mu g/m^3$ (W); 14,900 (C)
Naeher *et al* (2000)	Field test (Guatemala): background (B) open fire using (wood) (O) *plancha* stove (wood) (P) LPG stove (L) Test area – kitchen, bedroom, outdoors	Plancha and LPG reduce CO and TSP by 10-20% compared to open fire; *plancha* deteriorates with age. Kitchen values: $PM_{2.5}$ = 56 $\mu g/m^3$ (B) 528 (O) 96 (P) 57 (L) PM_{10} = 173 $\mu g/m^3$ (B) 717 (O) 210 (P) 186 (L) TSP = 174 $\mu g/m^3$ (B) 836 (O) 276 (P) 218 (L) CO = 0.2 ppm (B) 5.9 (O) 1.4 (P) 1.2 (L)

Fig. 4. Reducciones asociadas con la implementación de estufas eficientes. Fuente: Budds J., Biran, A., Rouse, J. (2001) What's cooking. A review of the health impacts of Indoor Air Pollution and technicals interventions for its reduction.

En nuestro estudio, estamos adoptando una posición conservadora y esperamos reducciones del 40% en los niveles de contaminantes al interior de las cocinas y probablemente hasta un 30% de reducción en la exposición personal a $PM_{2.5}$ y CO (Ver Anexo 6 para una explicación detallada del esquema de muestreo y reducciones).

2.4 PROGRAMAS DE DIFUSIÓN DE ESTUFAS

La mayoría de los esfuerzos para combatir los problemas asociados a la contaminación de interiores se han encaminado a: a) la adopción de nuevas tecnologías, como las estufas eficientes que promueven el uso de combustibles más limpios, b) promover la ventilación en las cocinas o c) cambiar algunos hábitos en la preparación de alimentos, por ejemplo, el uso de ollas tapadas para disminuir los tiempos de cocción, reducir el consumo de combustibles sólidos y mejorar la eficiencia.

Las estufas eficientes de leña surgen por el interés de los gobiernos que reconocen la exposición a humo de leña como un problema serio de salud pública, especialmente en mujeres y niños pequeños (FAO, 2002). Después se suman los científicos y ambientalistas y en los años 90's, definen como tecnología apropiada aquella que promueva un desarrollo sustentable siempre y cuando tome en cuenta aspectos económicos, ecológicos y sociales a largo plazo y represente una mejora en la calidad de vida de los individuos, en armonía con los aspectos culturales y ambientales que los rodean (Díaz, 2002).

Desde los años 70's se han desarrollado e implementado diferentes modelos de EE para mitigar los niveles de contaminación intramuros, los tiempos de exposición al humo de leña y para disminuir el consumo de leña. Hay varios estudios que describen con detalle la experiencia del proceso de implementación de estufas, por ejemplo en China e India, donde se instalaron alrededor 170 y 300 millones de estufas con diferentes grados de adopción dependiendo de la comunidad (Zhang et al, WEA, 2000). Las EE presentan otro beneficio ambiental, disminuir la emisión de gases de efecto invernadero (Johnson et al, 2008) y promover una transición hacia combustibles más limpios (Masera, 1994). Los programas de difusión de EE en México han enfrentado muchos obstáculos (enfoques paternalistas, diseños con especificaciones técnicas no necesariamente ligadas a las prioridades de las usuarias, usos múltiples de combustibles y estufas) afectando a su vez los niveles de adopción y apropiación de la tecnología.

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CAPÍTULO 3
RESULTADOS

EMISIONES Y CONTAMINACIÓN INTRAMUROS

Para que la combustión sea eficiente y completa (que se produzca CO_2 y H_2O), deben minimizarse las pérdidas de calor a través de la cámara de combustión del dispositivo donde se quema la leña. Cuando alguna de las condiciones mencionadas previamente no se cumple (temperatura adecuada, disponibilidad de oxígeno y suficiente tiempo de permanencia de los compuestos para su oxidación completa), la combustión es incompleta y se genera un espectro muy grande de contaminantes con implicaciones perjudiciales al ambiente y a la salud de la gente expuesta al humo de leña. Además de estas condiciones, la combustión se ve afectada por otros factores como las propiedades físicas (capacidad calorífica, conductividad), químicas (reactividad, composición) y estructurales (tamaño de partícula, densidad, porosidad) del combustible, tamaño, forma y algunas otras características de operación (estacionalidad, distribución de la leña al interior de la cámara de combustión, patrones y periodos de combustión) (Tissari, 2008).

La combustión de biomasa en dispositivos de cocción es siempre ineficiente por lo que una parte del carbono contenida en el combustible se transforma en productos de combustión incompleta (PCI's) (Smith, 1987, Rogge et al., 1998). Se han establecido cinco categorías de contaminantes del aire en ciudades, de los cuales, la combustión de madera incluye a tres de ellos: Partículas suspendidas, hidrocarburos (compuestos orgánicos volátiles e hidrocarburos policíclicos aromáticos), monóxido de carbono y se ha incluido el formaldehído por ser un compuesto que se presenta regularmente y en concentraciones significativas durante la combustión además de que causa irritación de ojos, nariz y tracto respiratorio (Smith, 1987).

Fine et al (2000a, 2000b) identificaron más de 250 compuestos químicos en la caracterización de 6 especies de árboles al norte y sur de Estados Unidos. Mc donald et al (2000) identificaron 350 compuestos, incluyendo volátiles, semi-volátiles, inorgánicos, orgánicos en la combustión residencial de leña en Estados Unidos.

Para nuestro estudio, se realizará el monitoreo de Partículas de diferentes diámetros aerodinámicos monóxido de carbono y 8 hidrocarburos aromáticos policíclicos por las implicaciones que se ha demostrado tienen estos compuestos en la calidad del ambiente y la salud. A continuación se mencionan algunas características de cada uno de los contaminantes de estudio.

MONÓXIDO DE CARBONO

En condiciones normales de temperatura y presión es un gas inodoro, incoloro e insípido, un poco menos denso que el aire. Las fuentes naturales de CO en el ambiente son la oxidación del metano, el flujo de la superficie oceánica y la actividad metabólica de algunos organismos. Se remueve del aire por disolución en aguas de lluvia y por oxidación en las capas superiores de la atmósfera. La fuente más importante de producción de CO es por combustión incompleta de biocombustibles. La hemoglobina tiene cerca de 200 veces mayor afinidad por el CO que por el oxígeno, por lo que la carboxi-hemoglobina constituye una proporción cercana no solo a la concentración de CO en la sangre sino al tiempo de exposición al contaminante y al estatus fisiológico de la persona. El envenenamiento por CO consiste en una reducción de la concentración de Oxígeno en la sangre y por lo tanto falta de irrigación a los tejidos terminando en paro respiratorio. Utilizando el factor de emisión (cantidad de contaminante por unidad de masa de combustible quemado) se sabe que el CO tiene un factor promedio de 40g/Kg (Smith, 1987, Rogge et al, 1998).

PARTÍCULAS SUSPENDIDAS

Pueden clasificarse de acuerdo a su composición química, la distribución de sus tamaños, fuentes, impactos a la salud, solubilidad en los fluidos corporales o mecanismos para cuantificarlas. El término de partículas se refiere normalmente a la presencia de aerosoles y se da por un proceso mecánico o por condensación de gases (Lighty et al, 2000).

El mayor número de partículas en el humo por combustión de madera se encuentra en un diámetro de 0.01 μm, la superficie más grande está conformada por partículas de 0.2 μm y hay una distribución bimodal que incluye partículas de 0.3 y 10μm. En estaciones secas con viento, se ha encontrado una concentración total de partículas de 400-1000$\mu g/m^3$. El tamaño nos permite predecir acertadamente sus efectos potenciales en la salud así como el destino ambiental. Respecto a los niveles de deposición a lo largo del tracto respiratorio se sabe que partículas grandes se asientan principalmente en la parte nasofaríngea por el impacto normal de la inhalación mientras que las partículas de 0.01μm entran hasta la parte de los bronquios, donde el área de contacto está muy cerca y se depositan o asientan por mecanismos de difusión (Bi et al, 2003, Smith, 1987, Tissari, 2008).

Normalmente se miden partículas suspendidas totales (hasta 100μm) aún cuando sabemos que el tamaño de partículas que realmente se depositan a lo largo del tracto respiratorio (nasofaringe, bronquios y pulmones) es de 10-15μm. Se ha intentado cuantificar por separado las partículas suspendidas respirables, cuyo rango va de 2.5-3μm y se depositan por intercambio de gases en el área pulmonar e inhalables (aerosoles) de 10-15μm y se depositan en la parte superior del tracto respiratorio (Naeher et al., 2007).

La cantidad de partículas suspendidas disponibles para ser atrapadas por los filtros utilizados en ciclones o impactores, dependen de la temperatura, cuando es alta, hay una mayor fracción de partículas en la fase de gas que pasan a través de los filtros y cuando es baja se condensan y quedan atrapadas en el filtro. El factor de emisión promedio para este tipo de compuestos es de 2g/Kg (Smith, 1987).

En un estudio realizado por Saatkamp (2000) en Jarácuaro, México, se compararon las concentraciones de partículas suspendidas respirables y monóxido de carbono emitidos durante el proceso de combustión de leña con diferentes dispositivos: el tradicional fogón de tres piedras, estufa tradicional, elevada, Lorena y gas. La concentración promedio de partículas suspendidas en el fogón tradicional fue de 950 $\mu g/m^3$ y de 22 mg/m^3 de monóxido de carbono. La estufa Lorena presentó una reducción del 70% en la concentración de partículas suspendidas y un 50% en monóxido de carbono (Fig. 5).

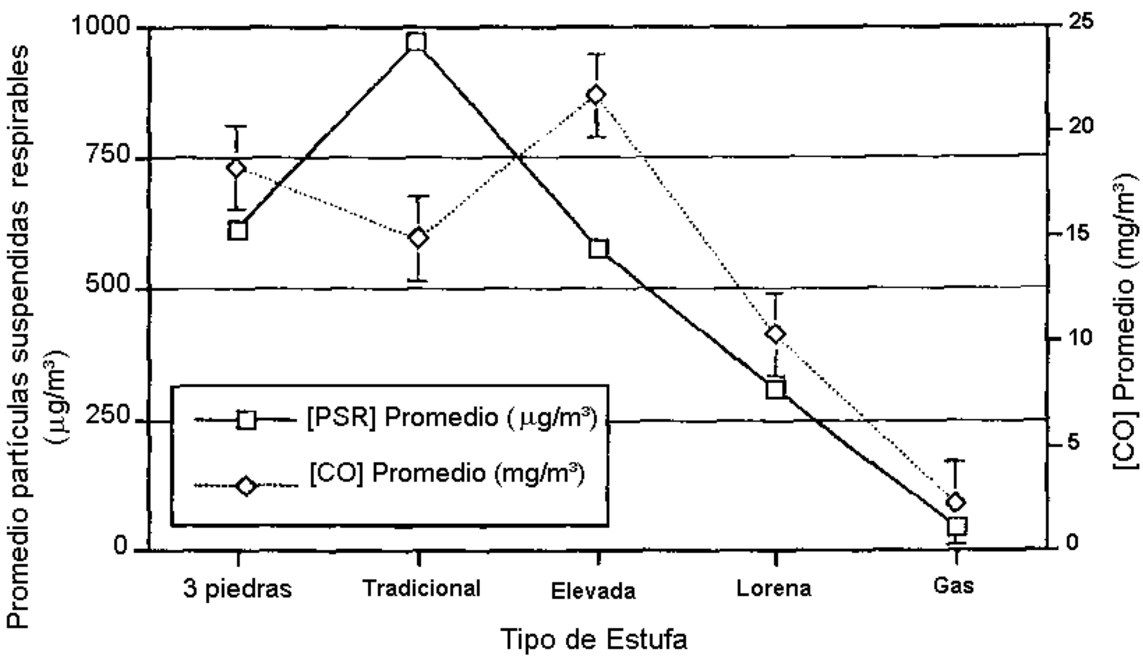


Fig. 5. Concentraciones promedio de partículas suspendidas respirables y monóxido de carbono según el dispositivo utilizado para cocinar. Fuente: Saatkamp B, Masera O, Kammen D.M. (2000) Energy and health transitions in development: fuel use, stove technology, and morbidity in Jaracuaro, Mexico. Energy for sustainable development, Vol. IV(2): 7-16..

Las concentraciones permitidas de partículas suspendidas según datos de la EPA, son 150 μ/m^3 para partículas PM_{10}, 65 μ/m^3 para $PM_{2.5}$ y 9 ppm para monóxido de carbono pero en muchos estudios de CI en México se ha demostrado que estas concentraciones se exceden hasta 50 veces (Brauer et al, 1996, Riojas-Rodríguez et al, 2001, Zuk et al, 2006).

HIDROCARBUROS AROMÁTICOS POLICÍCLICOS (PAHs)

Son compuestos constituidos por dos o más anillos de benceno fusionados. Dependiendo del peso molecular, pueden ser semi-volátiles o moléculas de alto punto de ebullición. Estos compuestos tienen estructuras muy complejas, diversas y pueden presentarse muchos isómeros; generalmente son lipofílicos. Para efectos de esta investigación, se discutirán únicamente las propiedades asociadas con los compuestos no-sustituidos. Estos compuestos se forman por la combustión incompleta de biomasa o hidrocarburos y su caracterización y cuantificación ha tomado una importancia central por la dependencia y el alto consumo de combustibles en las últimas décadas con fines industriales, para calefacción, cocción, transporte, etc (Smith, 1987, Böstrom et al, 2002).

La composición de las mezclas de PAHs depende de las propiedades inherentes del combustible y la tecnología utilizada para quemarlo. Los PAHs emitidos en forma de gas o ligados a partículas se oxidan y degradan en la atmósfera, proceso que se activa con la radiación ultravioleta y se potencia con la presencia de otros contaminantes del aire. La mayoría de los estudios de PAHs se han centrado en las emisiones generadas por el transporte vehicular urbano aunque muchos estudios confirman que la otra fuente importante de emisión es la quema de biomasa (Böstrom et al, 2002).

Numerosos estudios han relacionado la exposición a PAHs con efectos dañinos a la salud. La Agencia Internacional de Investigación en Cáncer (International Agency for Research on Cancer, IARC) los ha clasificado de acuerdo a su poder cancerígeno por la evidencia de tumores en humanos y animales experimentales expuestos en actividades ocupacionales En años recientes se ha demostrado que la exposición a benzo[a]pireno causa tumores en el estómago, esófago y lengua de ratones. Aunque hay estudios que sugieren que los PAHs pueden tener un efecto significativo en el sistema reproductor e inmunológico, el efecto crítico por la cantidad de evidencia acumulada durante décadas de investigación es su potencial cancerígeno (Böstrom et al, 2002)

Los niveles de PAHs en el ambiente son difíciles de estimar por la falta de métodos analíticos para su detección y la variabilidad en las condiciones de uso de los combustibles tanto en industrias como a nivel doméstico. Se estima que las emisiones anuales de PAH por consumo doméstico de aceite en Suecia constituyen aproximadamente el 20% respecto a las emisiones vehiculares. La quema de biomasa representa el 60% de las emisiones totales de PAHs en Suecia (Böstrom etal, 2002). Se han medido concentraciones de 100 a 200 ng/m^3 de PAHs en el centro de Estocolmo, Suecia. En México no se tienen estimaciones de la contribución de PAHs al inventario nacional de emisiones sin embargo la Red Ambiental de monitoreo atmosférico (RAMA), está desarrollando metodologías para incluir el monitoreo de algunos hidrocarburos en el 2011.

CAPÍTULO 3.1
IMPACT OF PATSARI IMPROVED COOKSTOVES ON INDOOR AIR QUALITY IN MICHOACÁN, MEXICO

(Artículo publicado)

El artículo presentado en este capítulo, corresponde a una publicación de la revista Energy for Sustainable Development y contiene una descripción detallada del proyecto de Implementación de estufas Patsari, el sitio de estudio, la selección de la muestra, el tipo de viviendas incluidas en el estudio y la metodología en la cual nos basamos para el monitoreo de contaminantes. Para ver una descripción detallada de las características de la meseta Purhépecha, las etapas del proyecto de implementación de estufas Patsari, el diseño de la tecnología y el equipo de gente que participó en el proyecto, consultar la tesis *"Manejo de recursos forestales en la región Purhépecha: diseño, difusión y adopción de tecnología para cocción con leña"* de Troncoso (2010). Para encontrar detalles específicos del diseño de la estufa Patsari, sus características y especificaciones técnicas, datos de eficiencia energética y consumo de leña, consultar la tesis de doctorado "*Evaluación energética del desempeño de dispositivos para cocción con leña*" de Berrueta (2007). Para ver la explicación detallada de los criterios y el modelo de selección de la muestra, consulte en Anexo 6. En el Anexo 5 se pueden consultar los formatos de campo utilizados para la recolección de información asociada con el monitoreo. En el Anexo 3 se presenta el cuestionario de tiempo-actividad con información relevante en materia de CI, condiciones de uso de la estufa, actividades de cocinado, variables demográficas y económicas de las usuarias, cantidad de combustible utilizado, etc.

Abstract

Hay muy pocas evaluaciones cuantitativas sobre el impacto de las extufas eficientes en México. La Asociación Civil "Grupo Interdisciplinario de tecnología rural apropiada" (GIRA, A.C.) ha implementado alrededor de 4,000 estufas eficientes, la mayoría de ellas en la región Purhépecha del Estado de Michoacán, México. En una sub-muestra de cocinas en una de las comunidades rurales de estudio, se realizó una comparación pareada antes y después de la implementación de las estufas y se obtuvo una reducción de 67% (n=33) y 66% (n=32) en las concentraciones 48-h de partículas finas ($PM_{2.5}$) y monóxido de carbono (CO) respectivamente. Las cocinas que presentaron las concentraciones más elevadas durante el muestreo inicial tuvieron las reducciones más dramáticas mientras que la variación total se redujo con el uso de la estufa. La Patsari es una alternativa efectiva para reducir la contaminación intramuros y su instalación representa beneficios potenciales para las familias rurales. Finalmente se realizaron varios estudios de monitoreo en materia de salud, emisiones, ambiental y social para analizar el

impacto de las estufas Patsari lo cual a su vez repercute fundamentalmente en el diseño y aplicación de políticas públicas quizá con mayor trascendencia que el impacto de la cantidad de estufas instaladas en estas comunidades.

Impact of Patsari improved cookstoves on indoor air quality in Michoacán, Mexico

Omar Masera

Grupo Interdisciplinario de Tecnología Rural Apropiada and Centro de Investigaciones en Ecosistemas
Universidad Nacional Autónoma de México (UNAM), Antigua Carretera a Pátzcuaro No. 8701
Colonia Ex Hacienda de San José de la Huerta, 58190, Morelia, Michoacán, Mexico
E-mail: omasera@oikos.unam.mx

Rufus Edwards

Department of Epidemiology, School of Medicine, University of California, Irvine, CA 92697-3957, USA

Cynthia Armendáriz Arnez and Victor Berrueta

Grupo Interdisciplinario de Tecnología Rural Apropiada and Centro de Investigaciones en Ecosistemas
Universidad Nacional Autónoma de México (UNAM), Antigua Carretera a Pátzcuaro No. 8701
Colonia Ex-Hacienda de San José de la Huerta, 58190, Morelia, Michoacán, Mexico

Michael Johnson

Department of Environmental Health, Science, and Policy, University of California, Irvine, CA 92697-7070, USA

Leonora Rojas Bracho

National Institute of Ecology/SEMARNAT, Periférico 5000, Colonia Insurgentes Cuicuilco, 04530
Mexico City, Mexico

Horacio Riojas-Rodríguez

National Institute of Public Health, Avenida Universidad No. 655, Colonia Santa María Ahuacatitlán, 62508
Cuernavaca, Morelos, Mexico

Kirk R. Smith

School of Public Health, University of California, Berkeley, CA 94720-7360, USA

Little quantitative monitoring and evaluation of the impacts of improved stoves have been performed in Mexico. Grupo Interdisciplinario de Tecnología Rural Apropiada (GIRA) has recently disseminated 4,000 improved Patsari cookstoves, most of them in the Purépecha region of Michoacán state, Mexico. In paired comparisons in a subset of kitchens in a single community before and after installation of an improved Patsari cookstove, 48-hour average kitchen concentrations of carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) were reduced by 66 % (n = 32) and 67 % (n = 33), respectively. Kitchens that had more elevated concentrations during the baseline measurements demonstrated more dramatic reductions, as the overall variability was reduced when the improved stove was used. Thus, the Patsari stove provides an effective means of reducing kitchen air pollution and potential benefits of installing these stoves are considerable. Although requiring significant additional resources, the Household Energy and Health (HEH) Project catalyzed a much broader investigation into health, climate, environment and societal impacts of Patsari stoves, which has had a greater impact on public policy than the direct impact of the number of improved stoves installed in these communities.

1. Introduction

There is strong evidence of the role of biomass smoke from unvented household stoves in developing countries in acute lower respiratory infections including pneumonia in children aged under 5 years and chronic obstructive pulmonary disease in adult women [Bruce et al., 2000, Smith et al., 2004]. The prevalence of these health impacts reinforces the critical need for well received interventions that effectively reduce exposures in rural populations. Although a number of improved cookstove technologies have the potential to significantly reduce emissions to the indoor environment, exposure reductions have often not been realized in practice due to barriers of cost, suitability for cooking tasks, and acceptance by local populations.

Although Mexico has experienced considerable economic growth and development, almost 80 % of the rural population, or about 27 million people, depend on wood for cooking, heating and other domestic tasks [Masera et al., 2005], resulting in significant exposure of the rural population to pollutants in wood smoke. Fuelwood still provides approximately 80 % of energy used by rural households and 50 % of total energy use in rural communities [Díaz, 2000], representing a considerable expenditure accounting for on average 15-20 % of household income in rural Mexican communities [Masera and Navia, 1997]. As with many other rural communities worldwide, women are most exposed to pollutants from wood smoke during cooking. In Mexican rural homes, making tortillas represents more than half of daily fuelwood consumption, and women spend between two and four hours per day on this task in close proximity to the stove, breathing smoke. Women who have home industries making tortillas to sell – up to 20 % of women in some communities – may spend as many as eight hours per day in these conditions [Masera, 1995].

Although installing a vented cookstove is often assumed to mitigate air pollution exposures associated with open fires, in practice the situation is often more complicated, especially during transitional phases of technology adoption, in which households frequently retain traditional stoves for specific cooking tasks, or use multiple fuels and stoves depending on prices, seasons and availability [Edwards et al., 2007b]. The need to monitor the actual improvements in indoor air quality in homes in rural communities as a result of installation of improved stoves is therefore critical in assessment of the benefits of the improved stove. Although improved stoves have been promoted in Mexico for 15 years primarily for saving wood and reducing deforestation [Masera et al., 2000], there has been little systematic evaluation of the improvements in air quality in rural homes as a result of improved stoves. The current study begins to address this shortfall as part of the Household Energy and Health (HEH) Project[1]

1.1. Traditional stoves in Michoacán

Cooking in this region of Mexico is typically performed on open fires surrounded by three stones (three-stone fires, TSFs) and open fires with U-shaped surrounds usually built by the users out of mud or clay. Although these devices take the form of a "U" or horseshoe, and "enclose" the fire to a certain extent in what might be considered a combustion chamber, they do not possess a flue or chimney to transport the smoke that is generated from the kitchen. Although the open fire is highly polluting and often fuel-inefficient, its versatility is much appreciated. It can be made easily, anywhere, anytime, by anyone, at nearly zero cost, uses fuel of nearly any size, and requires no long-term maintenance [Troncoso et al., 2007].

1.2. The Patsari improved wood-burning stove[2]

The Patsari was developed by GIRA AC, a Mexican NGO working with local groups and communities in the development, adaptation, and dissemination of biomass energy, agroecology, and community (social) forest management technologies and micro-enterprises since 1987[3]. GIRA is the leading Mexican NGO focused on wood-burning cookstove development and dissemination and has received several awards including a national forest conservation prize in 2001 and the Ashden Award on Health and Welfare in 2006[4]. At the policy level, GIRA has advised more than 50 other NGOs and government agencies on biomass energy and cookstove dissemination.

The Patsari stove was developed with a participatory approach to meet cooking needs, reduce wood consumption, vent smoke outdoors and to be acceptable and affordable to local populations. The Patsari departs from a modified Lorena cookstove that was previously disseminated in Mexico and has the following improvements: (1) optimized design of the combustion chamber and tunnels, (2) custom designed parts for durability, including a metal chimney support and a ceramic stove entrance; and (3) reduction in construction time and standardized inner dimensions. The cookstove is made in approximately 2 hours with the aid of a metallic mould that ensures that critical dimensions are maintained. Two models were originally disseminated, with one or two entrances to feed fuelwood, respectively. The former has one combustion chamber and uses a metal *comal* of 53 cm diameter[5] for cooking tortillas and is preferred by households combining fuelwood use and liquified petroleum gas (LPG) use. The second Patsari model has two combustion chambers. The main one usually supports a ceramic *comal* (preferred by other users) for making tortillas. The smaller chamber has a metal *comal* of 35 cm diameter designed for cooking other dishes, such as beans, and other tasks, such as boiling water. Both Patsari models include tunnels that conduct the combustion gases to secondary chambers used for "low power" cooking tasks, such as keeping food warm or warming water. Each chamber includes baffles to improve heat transfer between the *comal* and the gases, but does not have a grate.

The body of these two original Patsari models is made of a mixture of sand and mud and a small amount of cement. Two new stove models have been recently developed, which are intended to cover, on the one hand, the needs of tortilla vendors (Patsari-tortillera) and, on the other, to provide more durability and less maintenance (Patsari-brick). All the materials for the four models are available locally, the custom-made stove parts are also manufactured by local small industries.

1.3. Dissemination program in the Purépecha region

A total of 4,000 stoves have been disseminated by GIRA, mainly in the Purépecha region of Michoacán, central Mexico, but also in eight other Mexican states. Figure 1 shows a conceptual diagram of the integrated stove development and dissemination approach used for the Patsari (Figure 2, which has photographs of a traditional stove and a Patsari), relying on a user-centered approach that seeks sustainable market-based operation at the regional level. GIRA acts as a facilitating agent and also conducts the overall monitoring and quality assurance of the dissemination process.

Stove monitoring and evaluation has been a critical component of the stove dissemination process since inception of GIRA's rural energy program fifteen years ago.

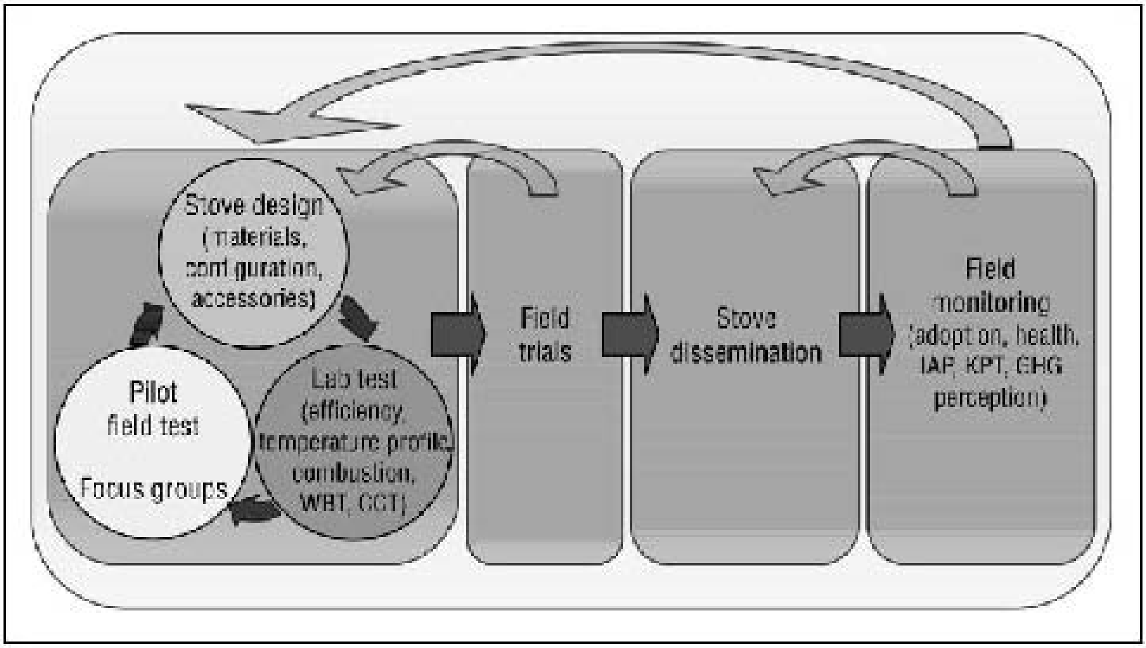


Figure 1. Conceptual diagram of integrated stove development and dissemination
WBT = water boiling test; CCT = controlled cooking test; KPT = kitchen performance test; IAP = indoor air pollution; GHG = greenhouse gas emissions

as this was recognized as an integral element within a dynamic process of stove innovation, development, and dissemination. More recently monitoring and evaluation was recognized by both funding and government agencies as critical in evaluating the benefits of stove projects in a scientifically acceptable manner and took an even more prominent role within the Patsari project. Schematically, laboratory tests, field trials and pilot tests of prototypes through participation of users' groups provided direct feedback to stove design. Subsequently field trials and field monitoring within communities 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 database including relevant data on stove construction as well as aspects related to stove adoption such as actual stove and fuel usage patterns, and maintenance and repair actions.

In the Patsari project, five monitoring and evaluation areas were identified to document both the major impacts of the Patsari stove and to obtain information on the stove innovation-dissemination chain. Table 1 presents summary information on the areas monitored and sampling procedure [GIRA, 2006]. This represents a unique effort to have a broad understanding of rural dynamics and potential benefits of the technology dissemination and adoption process and included monitoring health impacts in a 600-household study [Riojas-Rodríguez et al., 2006], an indoor air pollution survey [Armendáriz Arnez et al., 2007; Zuk et al., 2006], a stove performance study [Berrueta et al., 2007; Bailis et al., 2007, in this issue], a social perceptions study [Magallanes, 2006], and studies on fuelwood renewability [Ghilardi et al., 2007] and GHG emissions [Johnson et al., 2007].

Figure 2a. Traditional wood-burning cookstove

Figure 2b. Patsari wood-burning cookstove

Table 1. Areas of evaluation in the Patsari project

Study	Design	Sample groups	Evaluation endpoints
Health	Cross-sectional	300 control group homes 300 intervention homes with Patsari stoves	Spirometry, blood samples, and health symptoms
IAP	Before and after	60 households in one village 40 households in a second village	Personal exposures, kitchen concentrations and ambient
Social perception	Qualitative	23 focus groups 36 interviews with key informants	
Stove performance	Before and after	40 households for KPT 4 cookstoves using tortilla making in CCT 4 cookstoves compared for WBT	Both exclusive fuelwood and mixed fuelwood and LPG
GHG measurement	Cross-sectional	14 laboratory-based WBTs 22 field-based WBTs 14 Patsari households for KPT 8 open-fire households for KPT	Emissions of CO_2, CO, CH_4, N_2O, black carbon, and non-methane hydrocarbons

Notes

WBT: water boiling test; CCT: controlled cooking test, where a fixed amount of food is cooked by the same cook; KPT: kitchen performance test, involving typical cooking under normal conditions

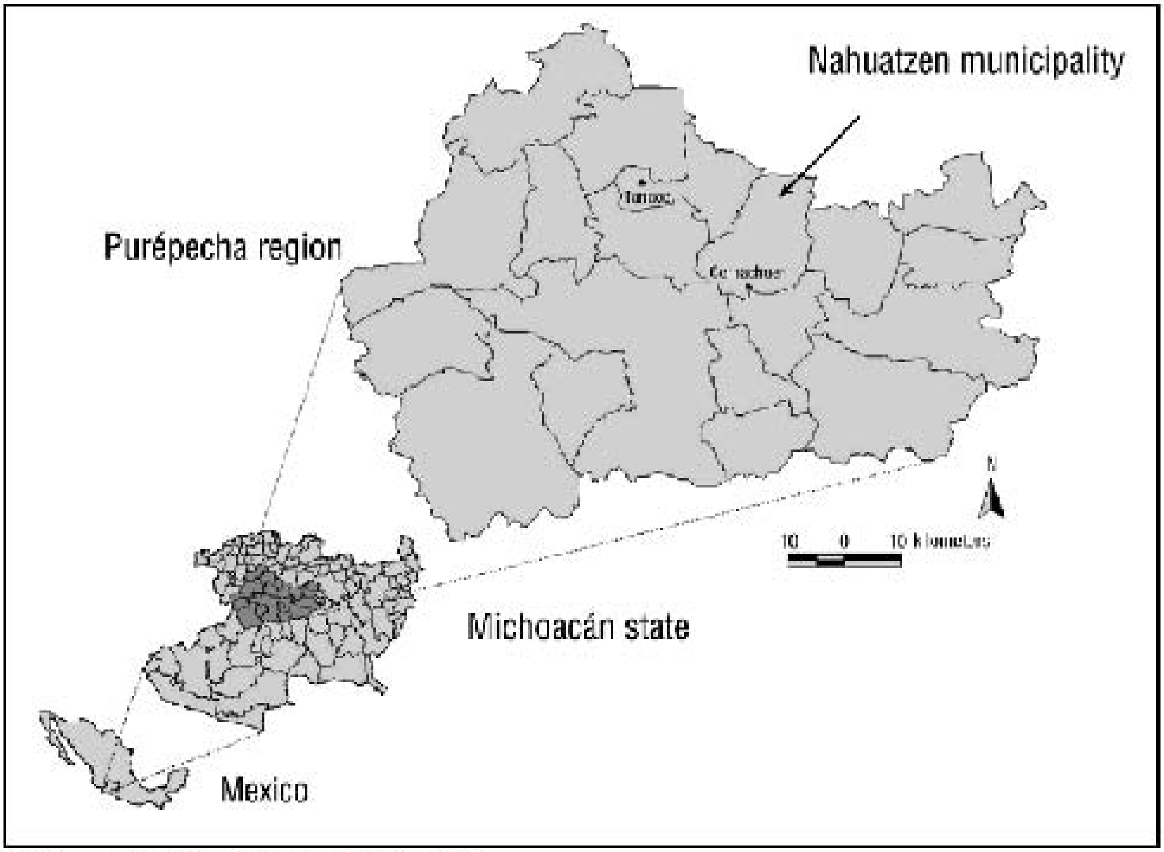


Figure 3. Map of the Purépecha region in Michoacán, Mexico

2. Data and methods

2.1. Study site description

In the Purépecha region (Figure 3) of the central Mexican highlands in Michoacán, 15 municipalities were selected where reliance on biomass fuels for primary energy provision was over 80 % [Masera et al., 2005]. From these municipalities, 600 homes were randomly selected in 6 Purépecha communities for participation in a community intervention trial of the effects of the improved Patsari stove on respiratory health effects and randomly divided into intervention and control groups. The study sample for investigation of the effects of the Patsari stove on indoor air quality (IAQ) was selected from the intervention group in the health study in one municipality, Comachuen, a remote indigenous agricultural community of 4,300 inhabitants located 2,600 m above sea level. Comachuen was selected as a large percentage of families rely on traditional cookstoves (TCSs) and wood for cooking (98 %) and there has been relatively little technology penetration in the community.

2.2. Study design

Investigation of the IAQ effects of the Patsari used a paired before-and-after study design in which baseline monitoring was performed for 48 hours with the traditional stove, and repeated later in the same season one month after installation of the Patsari and later [Edwards et al., 2007a, in this issue]. Sample size was estimated on the basis of a 10-home pilot assuming a coefficient of variation of 0.7 and a desire to detect at least a 40 % change in $PM_{2.5}$[6] and carbon monoxide (CO) concentrations after installation of the Patsari. Although a sample size of approximately 40 would have been sufficient to observe such differences, a sample size of 60 was selected to account for drop outs, those that did not install or were delayed in installing the improved stove, were unable to be located, migrated for work, or modified or otherwise had trouble with the normal functioning of the stove.

2.3. Household selection

As with many rural areas where housing is not standardized, a wide range of different stove and kitchen configurations was encountered in the Purépecha region. Since measurements of all kitchen types and stove arrangements were not feasible, given the sample sizes required to adequately represent all arrangements, a household screening survey was used to restrict kitchens to the more common arrangements in the region with the following criteria: enclosed by four walls, not shared between families, cooking used wood in TCS, families contained 5-9 members, and participating women stated a desire to use the Patsari stove after intervention. Most kitchens in Comachuen have wooden walls and a laminated roof, and around half have electric lighting. Human subject approvals were obtained from the University of California, Irvine, and from participating institutes in Mexico.

2.4. Indoor air pollution monitoring

$PM_{2.5}$ and CO was assessed in the kitchen, both before and after the introduction of the Patsari stove, at 1-minute intervals over 48 hours at a standardized height of 1.25 m above ground, 1 m distant horizontally from the central combustion zone, and at least 1.5 m from windows and doors.

Particulate matter was monitored using the UCB particle monitor (University of California Berkeley, Berkeley, CA, USA), a light-scattering nephelometer developed for use in rural biomass burning households [Edwards et al., 2006]. While the UCB does not select a traditional cutoff point, the photoelectric sensor is most sensitive to particles less than 2.5 µm in aerodynamic diameter ($PM_{2.5}$) [Litton et al., 2004], and has demonstrated good agreement with gravimetric $PM_{2.5}$ samples in field validation studies in rural homes [Chowdhury et al., 2007]. UCB monitors were adjusted for inter-instrument sensitivity through controlled tests in a combustion chamber at the field office in Mexico [Chowdhury et al., 2007], and calibrated for mass response to aerosols using co-located $PM_{2.5}$ gravimetric filter samples collected in kitchens [Armendáriz Arnez et al., 2007]. Average percentage difference in mass estimates between duplicate UCB samples was 14 %, with good agreement between different UCB monitors [Armendáriz Arnez et al., 2007].

Carbon monoxide was monitored using electrochemical CO sensors (HOBO® Onset Corporation Inc., Bourne, MA, USA). CO sensors were calibrated for inter-instrument sensitivity using gas calibration standards (0.5, 10, 25, and 60 ppm) before use in the study, and checked for response during 4 controlled combustion chamber co-locations during the course of the study (collocated with UCB particle monitors).

Both instruments contain dataloggers, which store the minute-by-minute data over the entire measurement period in their memories. These data are downloaded into a personal computer after monitoring.

2.5. Household post-monitoring questionnaires

Structured interviews with the cook in the household were conducted in Spanish at the end of the monitoring period to collect information on home and kitchen characteristics, stove use, fuel type, and other potential sources of $PM_{2.5}$ and CO.

3. Results

3.1. Household characteristics

Most houses had 3 to 5 rooms and almost all had electricity and piped water for kitchens and bathrooms. Although kitchens with 4 walls were selected there was still considerable variability in construction in houses that participated in this indoor air quality study, although the kitchens were more similar. The vast majority of kitchens had roofs of corrugated compressed particle board (approximately 6.5 mm thick, laminated on the outside to seal against water) and wooden walls, and 68 % had earthen floors, 19 % concrete floors and 12 % wooden floors. 75 % of homes had no windows in the kitchen and 25 % had a single window, although most left the door open while in the kitchen. Approximately 76 % of kitchens originally had the U-shaped traditional stove, and the remaining 24 % had TSFs.

As in many rural areas worldwide, cooking is invariably done by women, and typically women who are not cooking food to sell, reported spending 4 hours per day cooking, reducing on average to 3.5 hours after installation of the Patsari. Although those who prepare tortillas to sell may spend 8 hours or more per day cooking, these homes were not included in the current study. As the women in these homes are exposed to high concentrations for long periods, however, a type of Patsari stove has been developed specifically to reduce these exposures. Time spent cooking does not appear to be correlated to family

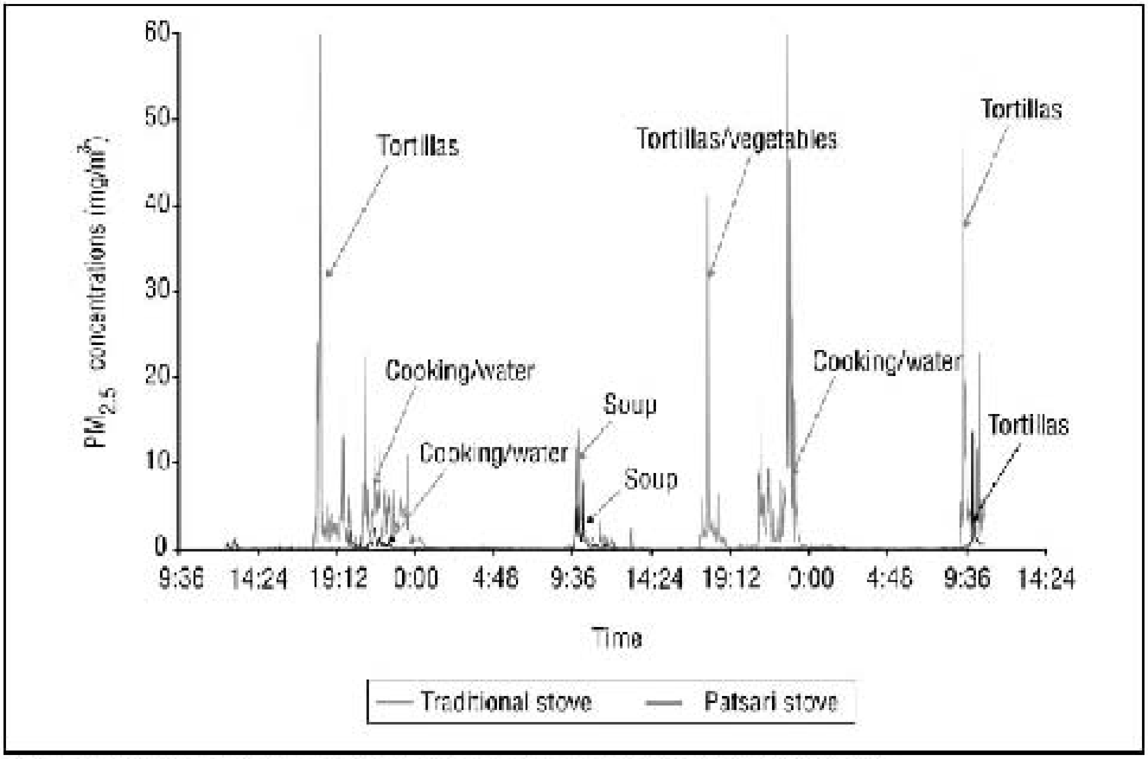


Figure 4a. Typical 48-hour 1-minute kitchen $PM_{2.5}$ concentrations before and after installation of the improved stove

size within this sample, although recall activity diaries may not have sufficient resolution to observe such differences. Rather, duratin of cookstove use per day appears to be more influenced by frequency of meals and specific dishes cooked. For example, 71 % reported cooking foods thrice a day, and 25 % cooking twice a day, and 25 % reported making tortillas once per day, 64 % twice per day and 11 % thrice per day, leading to large variability in hours spent cooking. On average 43 % of the time was spent cooking food with the traditional stove, 34 % was spent making tortillas and 23 % was spent frying food. In addition when *nixtamal*, the cornmeal base for making tortillas, is prepared approximately once a week, or beans and stews are prepared, cooking would be longer, and all homes reported using stoves to heat water. Gas usage even if the homes had gas stoves was infrequent and a single cylinder usually lasted more than 3 months. (A cylinder holds 30 kg and costs US$ 29.) Although families spend a considerable fraction of their income on cooking in rural Mexico, these families in Comachuen did not purchase fuelwood but collected it from nearby areas. In the vast majority of homes, wood was collected from local areas, principally by the husband once or twice each week, taking 1 to 4 hours. Trash was not burned and automobile traffic was relatively infrequent for most homes.

3.2. CO and $PM_{2.5}$ monitoring

Figures 4a and 4b demonstrate typical reductions in $PM_{2.5}$ and CO in kitchens during a 48-hour monitoring period before and after Patsari installation. Times that the stove was lit during the day are clearly identifiable, and start at 9:30 a.m. with the preparation of the morning meal. The evening meal is typically the large meal as the husbands are away at work during the day. The cooking fires generally stay lit through 11 p.m., when they are left to die out. For both $PM_{2.5}$ and CO dramatic reductions are seen with the installation of the Patsari stove.

Further, reasonably good agreement can be seen between CO and $PM_{2.5}$ peaks during the 48 hour period. The CO and $PM_{2.5}$ peaks occur together, as would be expected since both pollutants are produced during combustion. Since CO and $PM_{2.5}$ are produced to different degrees during flaming and smoldering combustion, the relationship between the two on a short time-frame is not exact, although they correlate well over 48 hour periods (Figure 5).

Table 2 shows the reductions in CO and $PM_{2.5}$ concentrations from paired comparisons before and after installation of the Patsari in 33 homes. Although some women continued to use a traditional stove in the same room, or in the yard, CO and $PM_{2.5}$ concentrations were still significantly reduced by 66 % and 67 % respectively compared to the traditional TCSs. In addition Figure 6 shows boxplots (this term is explained in the figure caption) of the distributions of kitchen CO and $PM_{2.5}$ concentrations for homes before and after installation of the Patsari. In these paired comparisons in the same homes, there was no overlap of values between the 25th and 75th percentiles before and after installation of the Patsari, showing reductions across the range as a result of the Patsari stove. In order to look at individual differences across houses

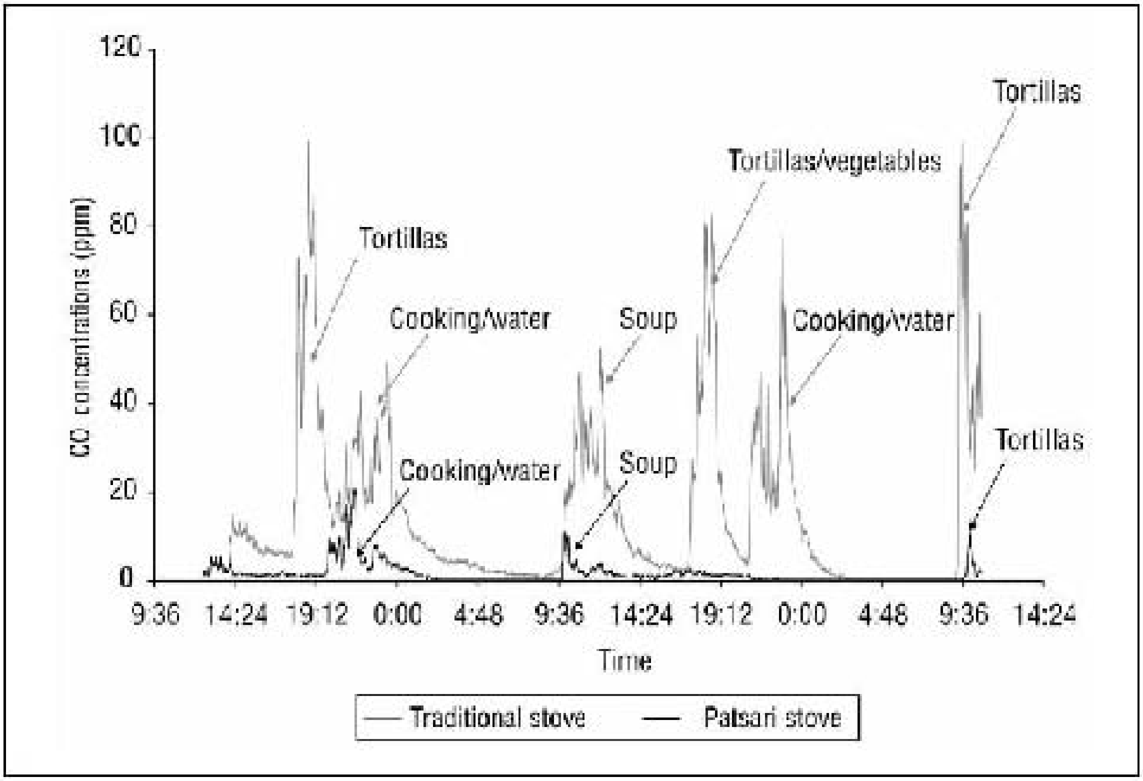


Figure 4b: Typical 48 hour 1 minute kitchen CO concentrations before and after installation of the improved stove

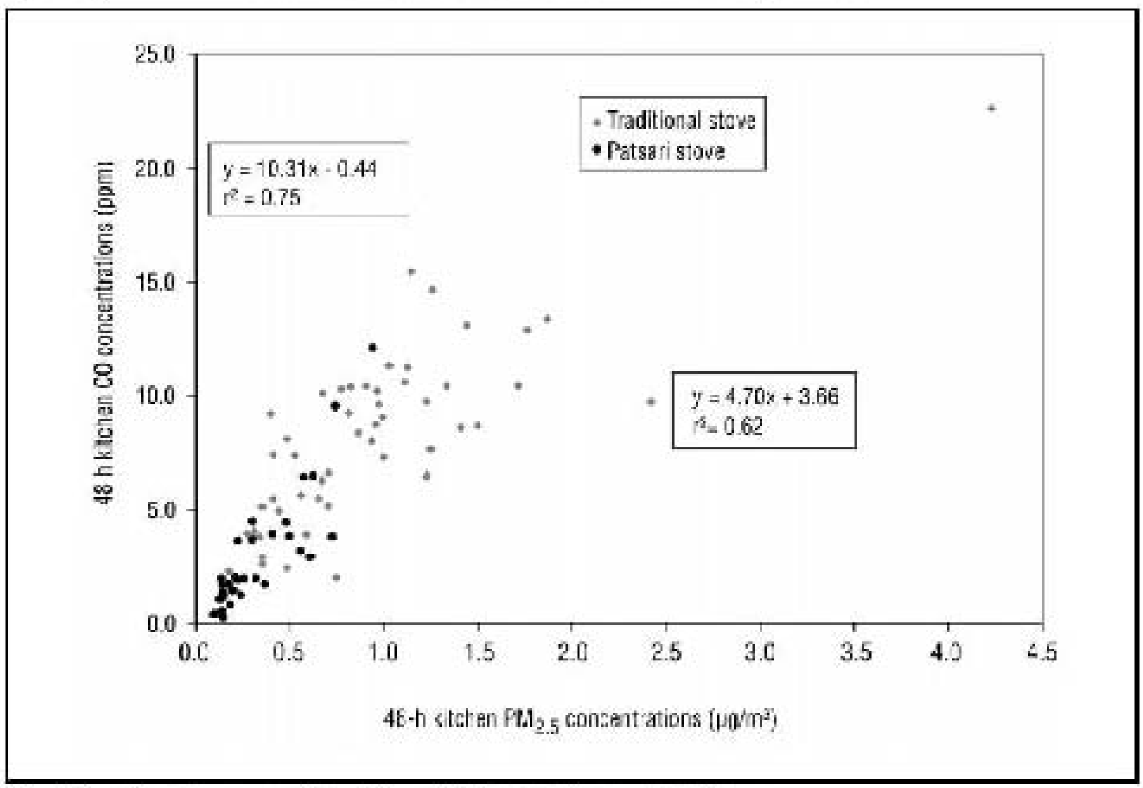


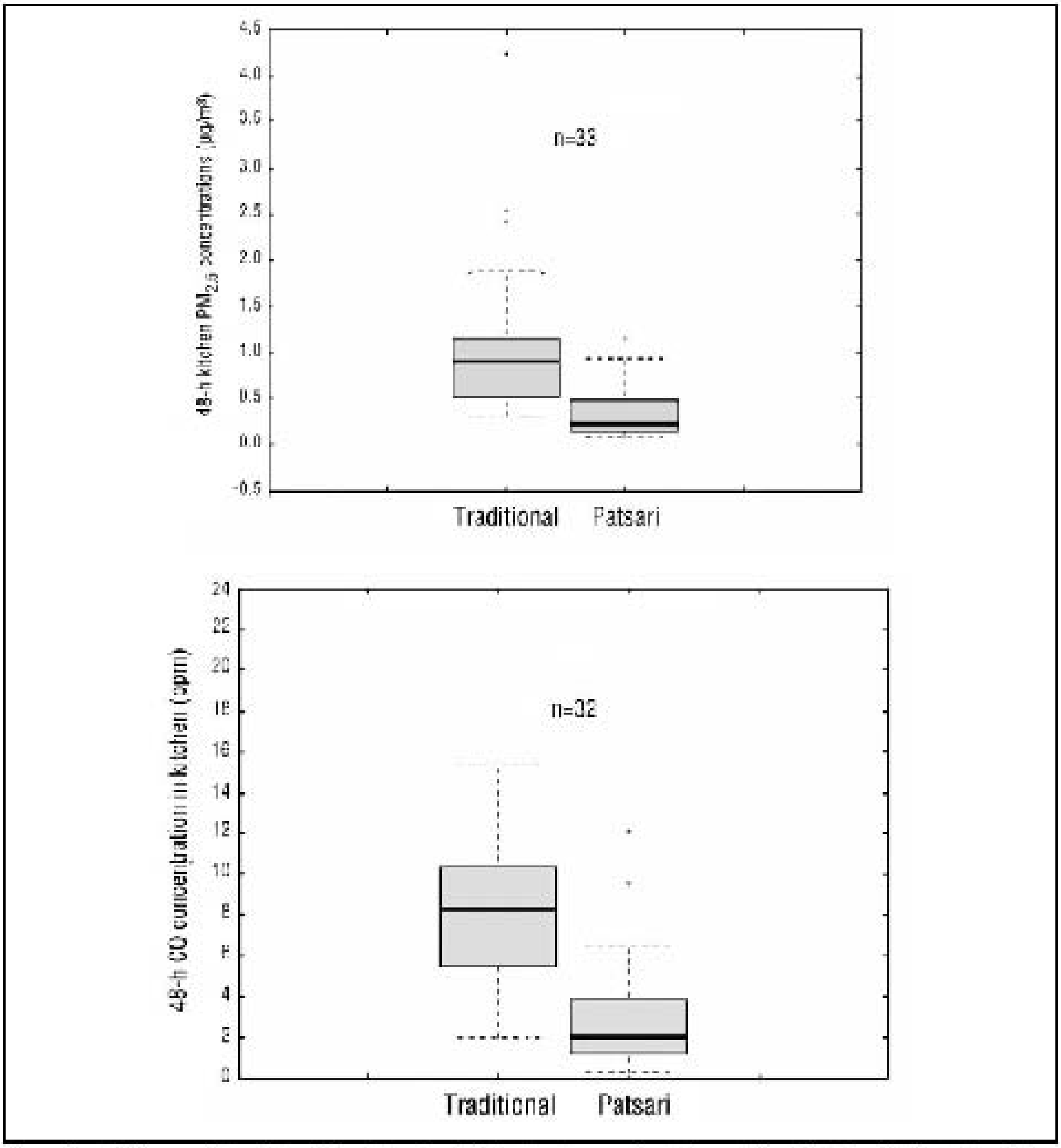
Figure 6. Correlation between average 48-hour $PM_{2.5}$ and CO for both traditional and Patsari stoves.

Table 2. GIRA: Patsari stove – paired before and after comparisons of 48 hour averages

	Before				After			Wilcoxon signed rank test[1]	Percentage change
	N	Average	Std. dev.	Maximum	Average	Std. dev.	Maximum		
PM (mg/m^3)	33	1.03	0.79	4.33	0.34	0.27	1.15	< 0.001	67
CO (ppm)	32	8.98	4.44	22.61	3.02	2.86	12.09	< 0.001	66

Note

1. Wilcoxon signed rank test is a non-parametric (the underlying shape of the distribution of concentrations is not assumed) test for before and after samples based on the statistical probability of observing the ranked differences in the before and after measurements



Figures 6a and 6b. Average 48-hour kitchen $PM_{2.5}$ (a, above) and CO (b, below) concentrations before and after installation of the Patsari stove. These are boxplots, here the darker central line in the box represents the median concentration, the lower and upper boundaries of the box represent the 25th and 75th percentiles respectively, and the dashed lines above and below represent the range of values, with extreme values and statistical outliers appearing as individual points.

Figure 7 shows a comparison of the individual kitchen reductions in relation to the average 48 hour concentrations measured with the traditional open fire stove types. Figure 7 shows clearly that the magnitude of the reduction in each kitchen was closely related to the initial baseline levels with the TCS, with greater reductions in homes that had higher initial concentrations.

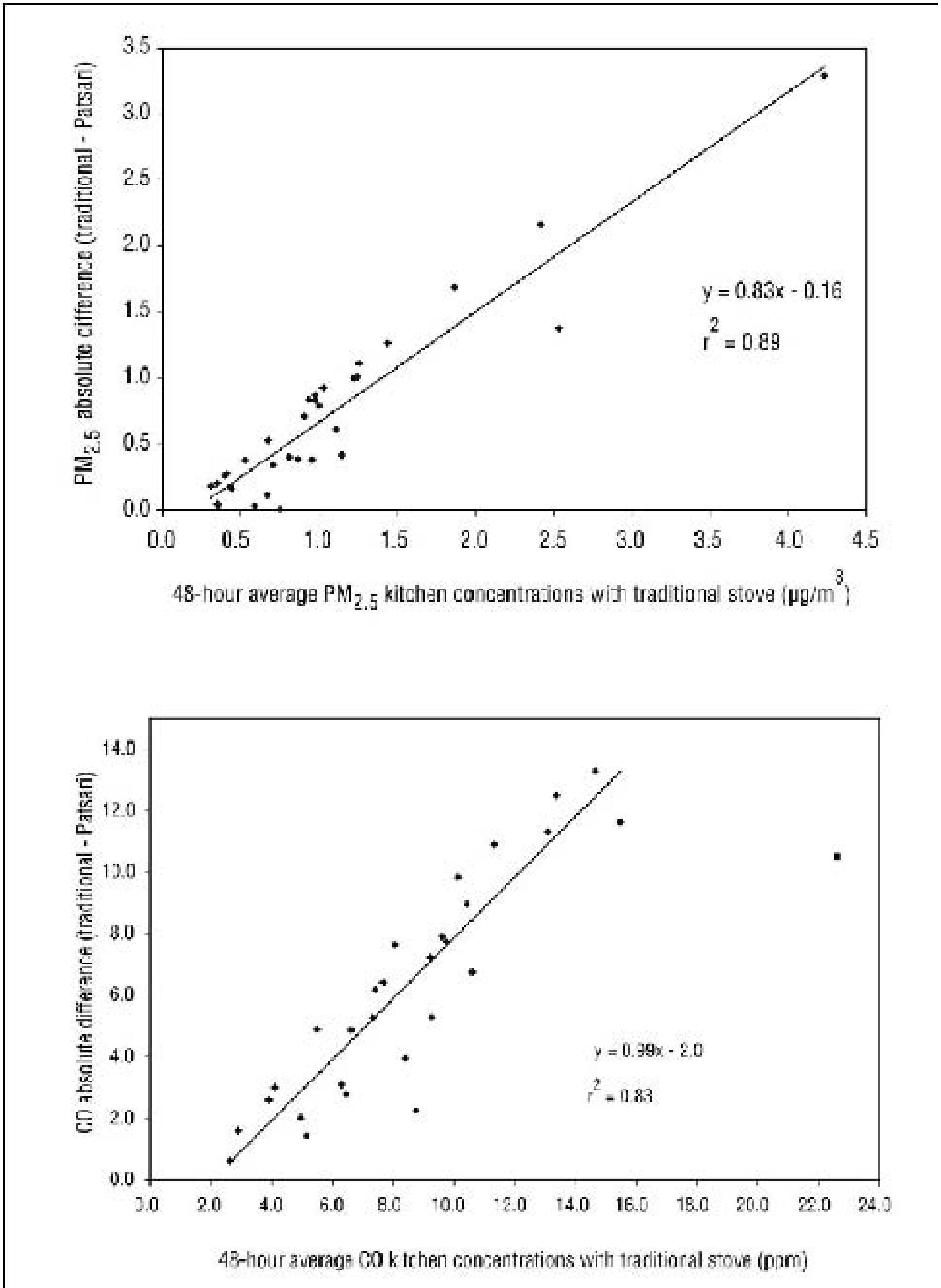
4. Discussion

In paired comparisons the overall average $PM_{2.5}$ and CO reductions observed as a result of installing the Patsari were 66 % ($p < 0.001$) and 67 % ($p < 0.001$) respectively (Table 2). Perhaps more importantly, however, the Patsari stove reduced kitchen concentrations across the distribution of homes in fairly consistent levels, and increasing reductions were seen in homes with higher initial concentrations with the open-fire stoves. Although these homes and communities relied predominantly on wood as the most important cooking fuel, gas, *olotes* (corn husks) and sawmill/carpentry residues were also used as secondary fuels in some homes. From an IAP perspective this complicates sampling designs, but multiple fuel usage is probably the most common situation in rural communities depending on season, agricultural products etc., as demonstrated in homes in China [Edwards et al., 2007b]. Since evaluating every combination of fuel usage is not feasible due to the large numbers of homes that would be required in order to maintain statistical power for such stratification, careful planning and preliminary surveys should be conducted in this regard before undertaking indoor air quality studies. Evaluation of the impact of the Patsari on kitchen concentrations should not be adversely affected due to the paired before and after design, and would reflect the actual adoption process of the stove.

Although because of resource constraints our sampling design did not include a control group in which no Patsari was installed to control for seasonal effects, in practice the use of a control group would have been limited, even controlling for housing type and family size, given (1) the diverse cooking patterns and cooking times between houses, (2) differences in fuel usage between homes, and (3) the different transitional stove adoption patterns where traditional stoves were still used to some degree in homes. Controlling for these factors would have entailed monitoring a prohibitively large number of control homes. Instead, the approach used in this study was to monitor the homes relatively soon after installation during similar climatic conditions to those when the traditional open fire stoves were monitored. It is possible a seasonal/temporal bias exists in the reductions seen here, but is unlikely given the relatively small changes in climatic conditions and the consistent linear relationship between the reductions in kitchen concentrations with the Patsari stove in relation to the initial concentrations with the open-fire stoves.

A disadvantage of the variability seen due to transitional stove adoption patterns, cooking patterns and fuel usage is that the reductions seen here as a result of the Patsari stove do not necessarily represent those in other communities. This community is likely to be at the lower end of potential reductions as technology penetration in the community is low, reducing the number of rapid adopter groups and tending to increase the degree of transitional stove adoption where the open fire stove is retained for some cooking tasks. In addition, in these homes the husband habitually collected firewood. The issue of stove promotion as a time saving technology is more complicated, therefore, as increased time spent cooking due to lower power output of stoves with covered combustion chambers would be perceived by the women of the home as being an increase in time taken to perform daily activities, as the principal time-saving would be for the husband in collecting firewood. Conversely, for houses that buy fuelwood, the benefits in reduced expenditures would be more apparent. Since success and adoption of the stove ultimately depend on users' perceptions, more targeted promotion matching stove benefits to users' priorities would ultimately result in a program with greater numbers of stoves in use. Although these homes may not necessarily be the homes where the greatest individual air pollution reductions are possible, the overall reductions of air pollution across the community would be greater as a result of more stoves in use. GIRA employs this approach in the analysis of adoption in communities, and the current focus is to identify characteristics of such adopter groups in longer term monitoring of homes.

The coefficient of variation of average 48 hour kitchen $PM_{2.5}$ concentrations remained at approximately 0.7 in both traditional TCS and Patsari homes, presumably due to continued use of a traditional stove in many homes as they transitioned to the new technology. In spite of efforts to constrain the variability through selection criteria of homes, therefore, the variability remained high due to differences in daily cooking habits. Initial statistical power analysis was conducted from a pilot study to estimate appropriate sample size to observe 40 % difference in kitchen concentrations using standard statistical criteria. The 40 % criterion was a subjective valuation determined on the basis of the high concentrations in homes using traditional open fire stoves, which if not reduced by 40 %, would not warrant the time, expense and effort of installing the improved stove as a technology to reduce air pollution in kitchens (although there may be other reasons for installing it, such as reduced fuel use). Although 30 % more homes were selected than would be determined by sample size calculations, in practice 7 participants withdrew after installation of the stove due to the monitoring requirements of the health and indoor air studies, with a further 2 unlocatable. 17 were not monitored for a variety of reasons including 4 that planned to build a new kitchen in which to house the new stove, a positive and not uncommon response to the new stove, although complicating monitoring designs, 2 had decided to move to another house and the husbands of 2 had migrated for work, resulting in moving to live with relations, 8 participants were not monitored as they requested additional training in the use of the stoves and the remaining participant had modified her stove so that it no longer



Figures 7a and 7b. Absolute reduction from traditional to Patsari stoves in relation to initial concentrations: (a, above) $PM_{2.5}$; (b, below) CO, with dat point at far right not included in regression line due to undue influence on the slope of the line represented the use of a Patsari. If the households of all of the original participants had been monitored the average reductions in kitchen concentrations would probably have been lower, but would not have reflected the potential benefits of use of the Patsari stove since the stove was not used as designed.

The potential benefits are shown by the systematic reductions made across all households with increasing reductions in kitchen concentrations in relation to the average 48-hour concentrations measured with the traditional open fire stove types (Figure 7). Thus, provided that sufficient training is given, and in spite of transitional adoption patterns in some homes where the traditional stove is retained for some tasks, reductions in kitchen concentrations would be expected across communities with the Patsari stove, proportional to their usage of the stove.

4.1. Benefits of the monitoring and evaluation conceptual approach

The monitoring and evaluation approach followed by GIRA resulted in a continual process of stove innovation – adaptation – monitoring – dissemination. As a result, the stove models tested in this paper have been further improved and the "Patsari-brick" is currently the stove model more commonly disseminated by the project. Although changes in stove models present difficulties for policy-makers and funders wishing to put a single value on the potential benefits achievable through improved cookstoves, the improvement of stove models represents a positive and valuable outcome of the monitoring and evaluation approach, showing the evolution of the technology through feedback on design.

In addition to the direct benefit of understanding the potential reduction in air pollution concentrations that would result in kitchens, a major largely unrecognized outcome of the HEH Project and the monitoring and evaluation approach was in bringing together both national and international collaborators to focus their efforts in understanding the social, environmental, health, indoor air, and greenhouse gas implications of the Patsari stove in a unique effort to monitor and assess all outcomes within the same communities. Although requiring significant additional resources, such efforts have generated new valuable data that allows an integrated evaluation of improved cookstove benefits. The monitoring studies have increased awareness in the Mexican government of indoor air pollution from biomass-burning as a problem requiring immediate action.

In addition, the Patsari project is the first project to our knowledge from the rural residential sector to demonstrate in-field emissions of greenhouse gases and among the first to market greenhouse-gas carbon credits in the private sector. The current and future impact of the results of this monitoring and evaluation approach on public policy is much larger, therefore, than the direct impact of the number of improved stoves installed in these communities, as they may benefit many rural communities throughout Mexico and possibly further afield.

Although there has been a tendency of government and funding agencies to focus on numbers of stoves disseminated, health benefits are dependent on consistent reductions in exposures, entailed by continued acceptance and adoption by local communities, since the health effects of most concern as a result of exposure to biomass smoke occur after chronic exposure, rather than as acute short-term effects. The success of a stove program ultimately is defined, therefore, by the numbers of stoves being used as intended in communities, rather than simply the number of stoves that are disseminated or built. Unfortunately, due to the long term nature of follow up in communities in order to assess chronic health end points, evaluations of the full impacts of these interventions are currently under-funded and -researched. Thus, although this paper addresses the first stage in this process in monitoring the indoor air pollutant reductions achieved by the intervention, more resources should be allocated to monitoring usage of the stoves and health impacts over time. Further, more resources should be allocated to identification of rapid adopter subgroups in communities where the benefits of the stoves are better perceived. This strategy will not only maximize the number of stoves in use in communities and the time and resources involved in the process, but will also aid in further dissemination of the stove through other adopter groups in the community. ■

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Notes

1. Health improvements, greenhouse gas emissions, and social and environmental impacts of the Patsari in the same area of Mexico will be reported elsewhere.
2. For more technical details about the Patsari stove see [Masera et al., 2005].
3. More information about GIRA can be found at http://www.gira.org.mx.
4. See http://www.ashdenawards.org/winners/gira.
5. A comal is a large metal or ceramic flat surface on which tortillas are cooked, which is sealed to avoid fugitive smoke emissions to the room.
6. $PM_{2.5}$ refers to particles that have a settling velocity less than a spherical particle with a diameter of 2.5 microns (µm) (aerodynamic diameter). In general the vast majority of combustion particles are less than 1 micron in diameter and smaller particles are thought to have greater health impacts.

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CAPÍTULO 3.2
REDUCTION IN PERSONAL EXPOSURE TO PARTICULATE MATTER AND CARBON MONOXIDE AS A RESULT OF THE INSTALLATION OF A PATSARI IMPROVED COOK STOVE IN MICHOACAN MEXICO

(Artículo publicado)

Abstract

Se evaluó el impacto de una estufa eficiente de leña (Patsari) en la reducción de las concentraciones microambientales y la exposición de partículas ($PM_{2.5}$) y CO en 60 hogares de una comunidad rural en Michoacán, México. Se encontró un promedio de $PM_{2.5}$ 24-h de 0.29 mg/m^3 en exposición personal y un promedio 48-h de 1,269 mg/m^3 en la concentración de $PM_{2.5}$ en la cocina de casas usuarias del fogón tradicional. Si estas concentraciones son típicas de las condiciones rurales en México, una proporción muy grande de la sociedad está crónicamente expuesta a niveles de contaminación intramuros que exceden entre 5 y 20 veces los límites en los que el gobierno mexicano ha encontrado efectos perjudiciales a la salud. La instalación de las estufas Patsari en estas comunidades reflejó una reducción del 74% en la mediana 48-h de la concentración de $PM_{2.5}$ en la cocina y 35% en la exposición personal; también se encontró una reducción de 77% y 78% en la mediana 48-h de la concentración de CO en la cocina y en la mediana 24-h de exposición personal respectivamente. La relación entre las reducciones de las concentraciones microambientales de la cocina y las reducciones en la concentración de exposición personal no solo cambiaron de acuerdo al tipo de contaminante sino también en función del tipo de estufa y más aún, respecto a la categoría de adopción. Si estas reducciones son típicas, se pueden cometer errores graves al utilizar las reducciones microambientales en la concentración de partículas como indicadores de exposición personal y sus respectivos efectos a la salud de las usuarias de leña cuando se evalúa el impacto de estos programas de intervención. Además la reducción en la exposición personal de CO fue significativamente diferente a las reducciones en $PM_{2.5}$ por lo que debe medirse específicamente exposición personal o las mediciones intramuros deben combinarse con diarios de tiempo-actividad, información que refleje de forma adecuada la contribución de cada concentración intramuros a la exposición personal.

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Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico

Abstract The impact of an improved wood burning stove (Patsari) in reducing personal exposures and indoor concentrations of particulate matter ($PM_{2.5}$) and carbon monoxide (CO) was evaluated in 60 homes in a rural community of Michoacan, Mexico. Average $PM_{2.5}$ 24-h personal exposure was 0.29 mg/m^3 and mean 48-h kitchen concentration was 1.269 mg/m^3 for participating women using the traditional open fire (fogon). If these concentrations are typical of rural conditions in Mexico, a large fraction of the population is chronically exposed to levels of pollution far higher than ambient concentrations found by the Mexican government to be harmful to human health. Installation of an improved Patsari stove in these homes resulted in 74% reduction in median 48-h $PM_{2.5}$ concentrations in kitchens and 35% reduction in median 24-h $PM_{2.5}$ personal exposures. Corresponding reductions in CO were 77% and 78% for median 48-h kitchen concentrations and median 24-h personal exposures, respectively. The relationship between reductions in median kitchen concentrations and reductions in median personal exposures not only changed for different pollutants, but also differed between traditional and improved stove type, and by stove adoption category. If these reductions are typical, significant bias in the relationship between reductions in particle concentrations and reductions in health impacts may result, if reductions in kitchen concentrations are used as a proxy for personal exposure reductions when evaluating stove interventions. In addition, personal exposure reductions for CO may not reflect similar reductions for $PM_{2.5}$. This implies that $PM_{2.5}$ personal exposure measurements should be collected or indoor measurements should be combined with better time–activity estimates, which would more accurately reflect the contributions of indoor concentrations to personal exposures.

Armendáriz Arnez Cynthia[1], Rufus D. Edwards[2], Michael Johnson[3], Miriam Zuk[4], Leonora Rojas[4], Rodolfo Díaz Jiménez[5], Horacio Riojas-Rodríguez[6], Omar Masera[1]
[1]Center of Ecosystems Research, Bioenergy, National Autonomous University of Mexico, Mexico, [2]Department of Epidemiology, University of California at Irvine, CA, USA, [3]Department of Environmental Health Science and Policy, University of California at Irvine, CA, USA, [4]Department of Urban, Regional and Global Pollution, National Institute of Ecology, Mexico City, D.F., [5]Department of Rural Energy, Interdisciplinary Group of Appropriate Rural Technology, Patzcuaro, Michoacan, Mexico, [6]Department of Environmental Health, National Institute of Public Health, Cuernavaca, Morelos, Mexico

Key words: Exposure bias; Biomass stoves; Indoor air pollution; Particulate matter; Carbon monoxide.

Rufus D. Edwards
Department of Epidemiology
School of Medicine
100 Theory, Suite 250
University of California
Irvine, CA 92697-3957
Tel.: (949) 824 4731
e-mail: edwardsr@uci.edu

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Practical Implications

Installation of improved cookstoves may result in significant reductions in indoor concentrations of carbon monoxide and fine particulate matter ($PM_{2.5}$), with concurrent but lower reductions in personal exposures. Significant errors may result if reductions in kitchen concentrations are used as a proxy for personal exposure reductions when evaluating stove interventions in epidemiological investigations. Similarly, time microenvironment activity models in these rural homes do not provide robust estimates of individual exposures due to the large spatial heterogeneity in pollutant concentrations and the lack of resolution of time activity diaries to capture movement through these microenvironments.

Introduction

Approximately half the world's population and up to 90% of rural households in developing countries still rely on solid fuels as their primary energy source (Bruce et al., 2000). Indoor solid fuel burning in open fires results in about 1.6 million premature deaths per year and represents near 4% of the global burden of disease, with a disproportionate burden falling on women and small children (Smith, 2006). Health effects of wood smoke have been comprehensively reviewed by Naeher et al. (2005), who found consistent evidence that biomass smoke increases risks of morbidity and mortality (Albalak et al., 2001; Smith and Ezzati, 2005; Von Schirnding et al., 2002). There is strong evidence for the role of indoor air pollution from unvented stoves in acute lower respiratory infections, the single most important cause of mortality in children aged under 5 years, chronic obstructive pulmonary disease, bronchitis and lung cancer (Bruce et al., 2000). In Mexico almost 80% of the rural population, or about 25 million people, depend on wood for cooking, heating and other domestic tasks (Masera et al., 2005) resulting in significant exposures of the rural population to pollutants in wood smoke, and a significant health burden (Riojas-Rodríguez et al., 2006). There is therefore a critical need for interventions to effectively reduce exposures of these populations. While there are a number of technologies that have the potential to significantly reduce emissions of air pollutants to the indoor environment, the exposure reductions have often not been realized in practice because of barriers of cost, suitability for cooking tasks and acceptance by local populations.

Although improved stoves have been promoted in Mexico for 15 years, primarily for reduction in fuel consumption and associated deforestation (Masera et al., 2000), there has been little systematic evaluation in Mexico of the reduction in indoor concentrations that result from installation of an improved stove. Even less information is available on the corresponding reduction in personal exposures, especially in situations where continued use of traditional stoves for some cooking tasks prevail. Most epidemiological research on the effects of biomass fuel use on health relies on questionnaire information on fuel and stove type, or the indoor concentrations measured over a 24-h period, which may not accurately characterize the exposure patterns of study participants. It is therefore important to assess reductions in kitchen and personal exposure concentrations relative to different stove usage patterns, and the relationship of personal exposure reductions to those seen in kitchen concentrations. Without careful assessment of these potential sources of bias, significant error may be incorporated when attributing pollutant concentrations to health effects in these populations.

The Patsari project represents a unique effort to obtain a broad understanding of rural dynamics (Berrueta et al., 2007), personal exposure reduction (Zuk et al., 2006), health effects (Riojas-Rodríguez et al., 2006), greenhouse gas emissions (Johnson et al., 2007), social and environmental impacts and evolution of the technology dissemination (Troncoso et al., 2007) and adoption process through the installation and evaluation of Patsaris in the state of Michoacan, Mexico. This paper addresses the reductions in personal exposures of women to $PM_{2.5}$ and CO in comparison with reductions in kitchen concentrations because of the installation of a vented Patsari stove.

Methods

Stove design

Similar to many rural areas worldwide, multiple types of stoves and combinations of fuels are used in Michoacan. The most prevalent of these stoves is the 'fogon', an open fire surrounded by a U shape of mud/brick/cement blocks with iron bars on the top on which is placed a 'comal' (a flat pottery dish or metal hotplate for cooking tortillas or other traditional maize dishes) or pots to cook (Figure 1a). The open side of the fogon is used to add fuel to the fire, and smoke is emitted directly to the room, as there is no flue or chimney. Henceforward we refer to the stove as the fogon or 'traditional' stove to distinguish it from the 'improved' stove or Patsari.

Fig. 1 Typical kitchens showing (a) traditional Fogon and (b) improved Patsari stove

The Patsari stove was developed for rural people as an alternative to the fogon with the following objectives: (a) affordable technology to meet cooking needs accepted by local populations, (b) diminish health impacts resulting from exposure to smoke in kitchens; (c) reduce wood consumption to mitigate the difficulty and expense associated with access to fuel wood.

The Patsari stove has a closed combustion chamber surrounded by bricks which are often decorated with ceramic tiles by the homeowners. A comal is integrally built into the surface of the stove, which has a smaller entrance for feeding fuel and a flue that passes through the roof and conveys the smoke outdoors (Figure 1b) (Masera et al., 2005).

Study site and sample population

In the central Mexican highlands in the state of Michoacan, 15 municipalities were selected where reliance on biomass fuels for primary energy provision was over 80% (Masera et al., 2005). From these municipalities 600 homes were randomly selected in six Purepecha communities for participation in a community intervention trial of the effects of the improved Patsari stove on respiratory health effects where families were randomly selected into intervention and control groups. The sample selected for estimation of reductions in personal exposures and indoor air pollution levels presented in this study was selected from the intervention group in Comachuen, an indigenous agricultural community of 4300 habitants located 2600 m above sea level, where the majority of families (98%) rely on traditional fogons and wood for cooking.

Study participants consisted of residents of 60 homes randomly selected from intervention homes where the kitchen was enclosed by four walls and were not shared between families; families contained between five and nine members; and participating women stated a desire to use the Patsari stove. The objectives were not to represent all possible family sizes and kitchen and stove arrangements in the community, which would have required a much larger sample size and cost, but rather to represent the enclosed kitchens that are common in the region. Figure 2 shows the typical distribution of rooms in a rural house in Comachuen. Protocols for inclusion of human subjects and informed consent procedures were approved by Institutional Review Board committee at the University of California at Irvine and from participating institutes in Mexico.

Fig. 2 Typical layout of home in Comachuen

Instrumentation

Particulate matter was measured using the University of California at Berkeley Particle Monitor (Berkeley, CA, USA) (henceforward referred to as UCB), a semi-continuous (1-min averages), light-scattering nephelometer (Edwards et al., 2006a,b). While the UCB does not select a traditional cutoff point, the photoelectric sensor is most sensitive to particles less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) (Litton et al., 2004). Laboratory validation of UCB particle monitor response in relation to particle size for monodisperse aerosols and combustion particles has been characterized by Edwards et al. (2006a,b). Field validation of the use of the UCB particle monitor to estimate $PM_{2.5}$ concentrations in biomass-burning kitchens has been presented by Chowdhury et al. (2007) including quality assurance measures collected during the course of the current study in Mexico.

To ensure comparability of the real-time $PM_{2.5}$ concentration estimates of the UCB, three quality assurance measures were undertaken: (1) as multiple instruments were deployed in different microenvironments, inter-instrument variability in aerosol sensitivity was adjusted over the course of the study in a series of four controlled co-locations within a cylindrical 1.5-m diameter steel combustion chamber using combustion aerosols generated by controlled combustion of small pieces of fuel wood collected from study homes. The methodology for the chamber testing is presented in detail in Chowdhury et al. (2007). Correlation between mean UCB mass and $PM_{2.5}$ gravimetric samples during the co-location chamber tests yielded R^2 values 0.98 or better, the slopes of which were used to normalize inter-instrument variability in response against gravimetric samples. (2) As nephelometer sensitivity is a function of an aerosol's specific optical properties such as size, color, and shape, calibration of UCB response with the target aerosol is required. Correlation between the normalized UCB photoelectric response and co-located 48-h $PM_{2.5}$ gravimetric measurements in 41 kitchens showed good agreement ($n = 41$, $R^2 = 0.90$), and was used to estimate $PM_{2.5}$ concentrations (Figure 3). (3) Duplicate samples in which two UCBs were co-located next to each other in the field home were collected in 28 homes (Figure 4). The average

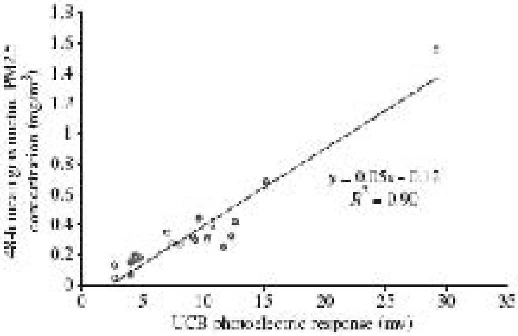

Fig. 3 Mass calibration of UCB against collocated $PM_{2.5}$ gravimetric samples

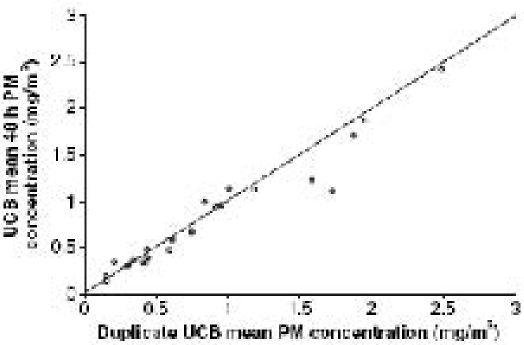

Fig. 4 Duplicate UCB 48-h mean measurements

percentage difference in 48-h average mass estimates between UCB duplicates was 14%, with good agreement between different UCB monitors (standard error 0.066; Pearson's $r^2 = 0.94$; $P < 0.001$).

Gravimetric $PM_{2.5}$ samples were collected using standard air sampling pumps (Model 224-PCXR8; SKC Inc., Eighty Four, PA, USA) with $PM_{2.5}$ cyclones (BGI Triplex Cyclone-BGI, Waltham, MA, USA) using a flow rate of 1.5 l/min. Flow rates were measured before and after installation of the sampling equipment in the home with a rotameter (Matheson Trigas, Montgomeryville, PA, USA), that had been calibrated using an SKC Ultra Flow bubblemeter (SKC Inc.). $PM_{2.5}$ particulate matter was collected on 37-mm, 2.0-μm-pore size Teflon filters (SKC Inc.). Filters were equilibrated for 48 h at 21 ± 2°C and 40 ± 5% relative humidity before being weighed on an electronic microbalance (Cahn Microbrobalance Model 29; Thermo Electron Corp., Waltham, MA, USA). Calibration of the microbalance response was checked with National Institute of Standards and Technology (NIST) certified calibration standards. Laboratory blank measurements were weighed before and after weighing of samples, and were within 5% of the average for all the periods. Field blank ($n = 7$) subtraction resulted in a 6.5% adjustment of the average increase in mass of the filters from the homes.

Carbon monoxide was measured using semi-continuous electrochemical CO sensors (HOBO®; Onset Corporation Inc., Bourne, MA, USA). Prior to sampling HOBO CO monitor response was compared with certified NIST traceable gas calibration standards at concentrations of 5, 10, 25 and 60 ppm (Scott Specialty Gases, Plumsteadville, PA, USA). HOBO CO monitors demonstrated good linearity against calibration standards (Pearson's $r^2 > 0.99$; $P < 0.001$). The slope of the response was different for each monitor, however, and was subsequently used to normalize inter-instrument variability in response relative to CO concentrations in gas calibration standards. Inter-instrument response was monitored in four controlled combustion chamber co-location tests to adjust for any changes over time during the monitoring period (collocated with UCB particle monitors).

Sampling design

$PM_{2.5}$ and CO concentrations were assessed during the dry season before installation of the improved Patsari stove and after 1 month of use.

Personal exposures. Semi-continuous $PM_{2.5}$ and CO personal exposures were assessed at 1-min intervals for a 24-h period; 24-h personal measurements were obtained by placing a UCB particle monitor and CO monitor in a small, locally purchased shoulder bag, which had been altered to allow airflow through a mesh surface. Because of the increased inconvenience of wearing personal exposure equipment, personal exposures were assessed for 24 h.

Microenvironment concentrations. Semi-continuous $PM_{2.5}$ and CO concentrations were recorded every minute for 48 h close to the stove, in the center of the kitchen, just outside the kitchen in the yard and in the main bedroom. Monitors close to the stove were placed at a standardized height of 1.25 m above ground, 1 m distant horizontally from the central combustion zone, and at least 1.5 m from windows and doors. Kitchen monitors were placed at least 2.5 m away from the stove and 1.5 m above the ground. The yard microenvironment was measured by placing UCB monitors 1.5 m above ground and as close as possible to where the family reported to spending the most time when outdoors. For 25% of homes stove microenvironments were monitored for 5 days to assess variability of 48-h measurements in relation to 5-day concentrations. In addition to semi-continuous measures, 48-h $PM_{2.5}$ gravimetric measurements were collected in kitchens for a subset of homes ($n = 41$), and ambient concentrations were measured throughout the study period on the roof of the local health clinic at the center of the community.

Structured interviews were conducted at the end of each 24-h period with a household questionnaire and time–activity log. Household questionnaires collected information on home and kitchen characteristics, stove use, fuel type, and other potential air pollution sources. For time–activity information participants were asked to remember and enumerate each cooking activity, duration, type of stove and fuel used and time spent in the kitchen during the day.

Statistical analysis

All data were analyzed with STATISTICA (Version 2001; StatSoft, Inc., Tulsa, OK, USA). Non-parametric Wilcoxon signed rank tests (SRT) were used to compare personal exposure and indoor concentrations before and after installation of the improved Patsari stove. Outliers and extreme values for boxplots were defined as values larger or smaller than four or seven times the standard error from the median respectively.

Results

Study participation

Although 60 homes were selected to characterize the reductions in mothers' personal exposures and kitchen concentrations in relation to stove usage patterns in homes that adopted the improved stove, it was anticipated that a number of these homes would not complete the study for a variety of reasons, including deciding not to install the improved stove. As drop out from the study may be unrelated to stove adoption, which is required to assess the overall impact of the improved stove intervention, the reasons for non-participation were assessed for each group and are presented in Table 1. A total of 26 homes were not monitored after the installation of the improved Patsari stove, of which four were no longer willing to participate because of the requirements of the health study, three were no longer willing to participate in the indoor air monitoring and two were unable to be located at the time of the post-installation monitoring. Of the remaining 17 homes, monitoring was not conducted in eight because either a new kitchen was built to house the patsari or because the participants changed homes. Monitoring was also not conducted in a home that had modified the Patsari by removing the comal. The remaining eight homes had problems adapting to the requirements of the stove and had not adopted the Patsari.

Table 1 Participation rates for baseline and post-monitoring campaigns

Baseline measurements of traditional fogon	60
Monitored post-Patsari installation	34
Not monitored post-installation	26
Withdrew participation	
Health	4
Indoor air monitoring	3
Unable to be located	2
Not monitored	
Were building new kitchen	4
Plans to move to another house	2
Husband migrated – moved in with relative	2
Requested additional training	4
Problems with stove requirements	4
Modified improved stove	1

Reductions in personal exposures

Particulate matter. Average 24-h personal exposures to $PM_{2.5}$ for women using the traditional fogon were 0.29 mg/m^3 for all 60 participating women. Table 2 and Figure 5 show personal exposures to $PM_{2.5}$ for homes that adopted the Patsari stove both on an aggregate level and stratified by stove usage patterns, where participants retained a traditional fogon in the same room, another room, or the yard mainly for heating bath water and cooking of nixtamal.[1] On an aggregate basis for those with paired before and after measures median 24-h personal exposures were 0.17 mg/m^3 for women with a traditional fogon and 0.11 mg/m^3 with an improved Patsari. This represents a 35% reduction ($P < 0.0001$) in median personal exposures to $PM_{2.5}$ notwithstanding differences in stove adoption patterns (Table 2). For individuals who adopted the improved Patsari stove exclusively, median reductions were greater at 38% ($P < 0.04$; Table 2). As would be expected little reduction in the median $PM_{2.5}$ personal exposure concentrations was seen when another traditional stove was present in the same room (2%, $n = 11$). When the traditional stove was in the yard, or another room, a median reduction in personal exposure was still observed although less than that of exclusive Patsari users (27%, $n = 9$). The lack of statistically significance for comparisons when a traditional stove was retained also reflects the low sample numbers when stratified by stove user group. In addition to reductions in the median concentrations, the variability in $PM_{2.5}$ personal exposures was reduced for exclusive Patsari users, and those who had a traditional stove outside or in the yard, when compared with the traditional stove and those participants who had a Patsari and traditional stove in the same room. Maximum 24-h average exposures for exclusive Patsari users and those with a Fogon outside or in another room were also similarly reduced, while the maximum with a traditional stove in the same room remained at levels similar to those seen before installation of the improved stove.

[1]Nixtamal is a corn base cooked once a week and subsequently used daily for cooking tortillas, the traditional Mexican accompaniment for daily meals.

Table 2 Reductions in $PM_{2.5}$ 24-h personal exposures and 48-h kitchen concentrations after installation of the Patsari improved stove

		Before				After				Wilcoxon SRT	% Change
PM (mg/m³)	N	Average	Median	s.d.	Maximum	Average	Median	s.d.	Maximum	P-value	Median
Personal exposure											
All participants	23	0.26	0.17	0.20	0.60	0.16	0.11	0.15	0.63	<0.001	35
Patsari only	6	0.10	0.15	0.09	0.16	0.13	0.13	0.05	0.11	<0.04	10
Patsari with fogon inside kitchen	11	0.25	0.21	0.10	0.52	0.22	0.19	0.17	0.63	NS	2
Patsari with fogon outside	6	0.25	0.15	0.23	0.50	0.14	0.11	0.05	0.33	NS	27
Kitchen concentration											
All participants	33	1.02	0.91	0.79	4.23	0.35	0.24	0.27	1.15	<0.001	74
Patsari only	7	1.04	1.00	0.70	2.53	0.32	0.21	0.37	1.13	<0.03	79
Patsari with fogon inside kitchen	14	1.35	1.20	1.05	4.23	0.58	0.50	0.24	0.96	<0.01	30
Patsari with fogon outside	12	0.75	0.72	0.20	1.10	0.22	0.20	0.20	0.76	<0.01	60

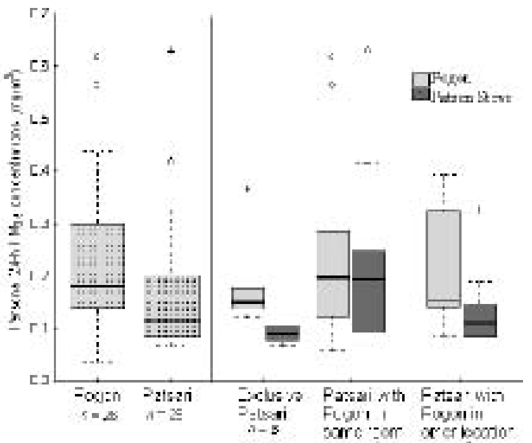

Fig. 5 UCB $PM_{2.5}$ 24-h personal exposure reductions before and after installation of the Patsari improved stove and stratified by stove usage patterns

Carbon monoxide. Average 24-h CO personal exposures for women using the traditional fogon were 2.35 ppm ($n = 60$). Table 3 and Figure 6 show CO personal exposure reductions for homes that adopted the Patsari stove both on an aggregate level and stratified by stove usage patterns. On an aggregate basis for those with paired before and after measures ($n = 24$), median personal exposures with the traditional stove were 2.3 ppm for women with a traditional fogon and 0.5 ppm with an improved Patsari, respectively. This represents a 78% reduction in median personal exposures notwithstanding differences in stove adoption patterns (Table 3). For individuals who adopted the improved Patsari stove exclusively the reduction in median personal exposures was 54% (Table 3). For those with a traditional stove retained in the kitchen reductions were 78% and for those with a traditional stove in another room or in the yard the reductions were 86%. Similar to the pattern of $PM_{2.5}$ exposures, maximum 24-h average exposures for those who retained a traditional stove in the same room remained similar to levels seen before installation of the improved stove. For improved stoves where a traditional stove in the same room was not present, maximum 24-h exposures were considerably reduced compared with traditional stoves. Similar patterns were seen in reduction of variability in 24-h average personal exposures.

Reductions in kitchen concentrations

Particulate matter. Mean 48-h $PM_{2.5}$ kitchen concentration in homes with the traditional fogon was 1.27 mg/m³ ($n = 60$). Table 2 and Figure 7 show $PM_{2.5}$ kitchen concentrations for homes where the

Table 3 Reductions in CO 24-h personal exposures and 48-h kitchen concentrations after installation of the Patsari improved stove

		Before				After				Wilcoxon SRT	% Change
CO (ppm)	n	Average	Median	s.d.	Maximum	Average	Median	s.d.	Maximum	P-value	Median
Personal exposures											
All participants	24	2.7	2.3	2.1	8.3	1.0	0.5	1.8	8.3	<0.001	78
Patsari only	5	1.3	1.3	0.7	2.4	0.7	0.6	0.4	1.4	NS	54
Patsari with fogon inside kitchen	11	2.7	2.3	2.1	7.6	1.6	0.5	2.5	8.3	<0.02	78
Patsari with fogon outside	8	3.6	3.5	2.4	8.3	0.6	0.5	0.3	1.0	NS	86
Kitchen concentrations											
All participants	32	8.9	8.8	4.4	22.8	3.0	2.0	2.7	12.1	0.05	77
Patsari only	7	7.0	7.3	5.5	16.3	1.6	1.2	1.1	3.7	<0.04	83
Patsari with fogon inside kitchen	13	10.0	10.6	5.7	22.6	3.5	3.3	2.7	12.1	<0.01	69
Patsari with fogon outside	12	7.4	8.8	2.1	11.3	2.1	2.0	2.1	9.5	<0.02	76

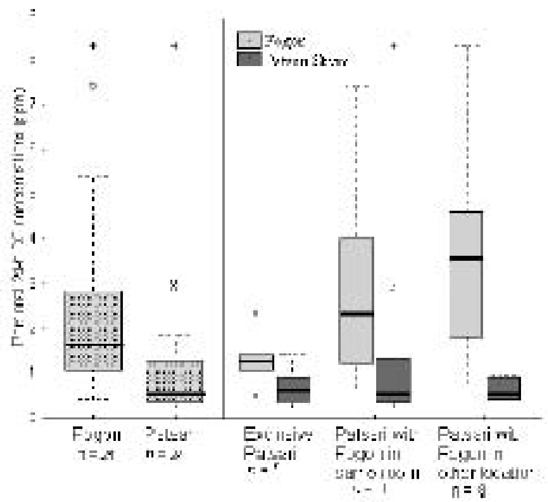

Fig. 6 24-hour CO personal exposure reductions before and after installation of the Patsari improved stove and stratified by stove usage patterns

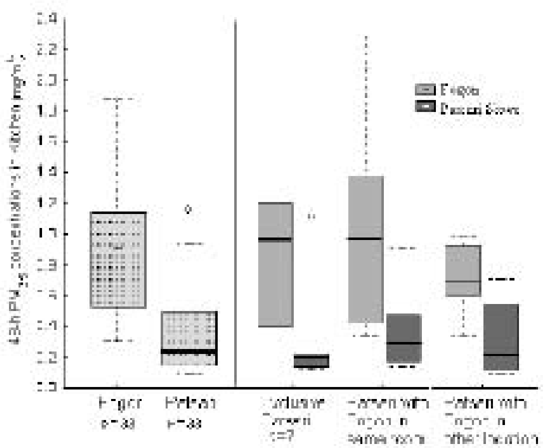

Fig. 7 48-hour $PM_{2.5}$ concentrations in kitchens before and after installation of the Patsari improved stove and stratified by stove usage patterns

Patsari stove was adopted both on an aggregate level and stratified by stove usage patterns. On an aggregate basis for those with paired before and after measures (n = 33), median 48-h kitchen concentrations were 0.91 mg/m^3 with a traditional fogon and 0.24 mg/m^3 with an improved Patsari. This represents a 74% reduction in median 48-h kitchen concentrations notwithstanding differences in stove adoption patterns. For homes that used the Patsari stove exclusively, the reduction in median 48-h CO kitchen concentrations was 79%. For homes where a traditional stove continued to be used in the kitchen, the reduction in median concentrations was 70% and when a traditional stove continued to be used outside or in another room, the reduction in median concentrations was 68%.

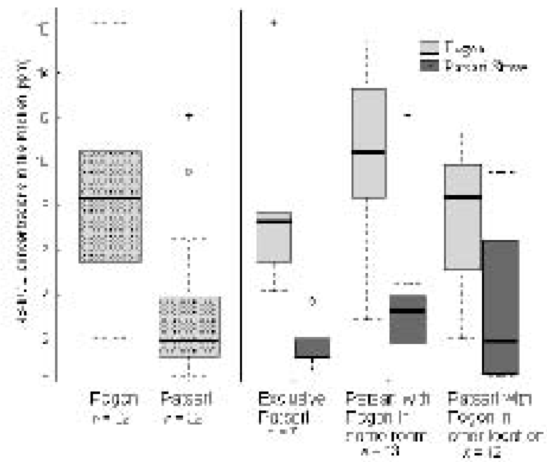

Fig. 8 48-hour CO concentrations in kitchens before and after installation of the Patsari improved stove and stratified by stove usage patterns

Carbon monoxide. Mean 48-h kitchen CO concentration in homes with the traditional fogon was 8.2 ppm (n = 60). Table 3 and Figure 8 show kitchen concentrations for homes where the Patsari stove was adopted both on an aggregate level and stratified by stove usage patterns. On an aggregate basis for those with paired before and after measures (n = 32), the median 48-h kitchen concentration for women with a traditional fogon was 8.6 and 2.0 ppm after installation of an improved Patsari, respectively. This represents a 77% reduction in kitchen concentrations notwithstanding differences in stove usage patterns. For individuals who adopted the improved Patsari stove exclusively the reduction in median kitchen concentrations was 83%. For those with a traditional stove still in the same room the reductions were reduced to 68%, and for those kitchens with a fogon in another location reductions were somewhat greater (76%) in comparison.

48 h averages vs. 5 day averages

$PM_{2.5}$ kitchen concentrations were monitored (using semi-continuous UCB monitors) for approximately 5 days in a sub-sample of 24 of the 60 homes with a traditional fogon and 10 of the 34 homes after installation of the Patsari to estimate the extent that 48-h sampling times in the rest of the homes represented the longer sampling period. As sampling times were slightly short of the complete 5 days of sampling we restrict our analyses to four complete 24-h periods to better assess variability. Figure 9 shows the reduc-

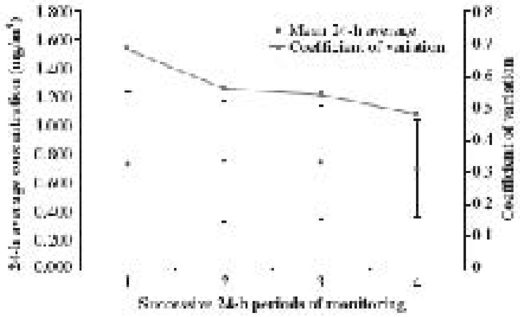

Fig. 9 Reduction in coefficient of variation (COV) associated with successive 24-h periods of monitoring for 24 homes with traditional fogons

Note: Error bars represent the standard deviation of 24-h average $PM_{2.5}$ concentrations for homes with traditional fogons, which is reduced with inclusion of each successive 24-hour period into the monitoring average.

tion in variability of average $PM_{2.5}$ estimates in homes using a traditional fogon as successive 24-h periods are included. The coefficient of variation (COV) of the mean $PM_{2.5}$ concentrations for the 24 homes reduced from 0.68 for one 24-h period to 0.48 for the 4-day period; 60% of this reduction occurred in the first 48 h. Similarly, for homes using the Patsari stove with four complete 24-h periods of $PM_{2.5}$ monitoring, the COV reduced from 0.70 to 0.55, with 54% of the reduction occurring during the first 48 h.

Discussion

Although there have been improved stove dissemination projects in Mexico since the 1980s there has been little formal in-field evaluation of the effectiveness of the intervention in reducing exposure to indoor air pollution. While efficacy measurements that test indoor air reductions in controlled settings give an idea of the maximum achievable benefit, it is critical that in-field evaluations are also performed to assess actual impacts for different stove usage groups in communities where the stove is adopted. Such assessments, of course, are much more difficult and complex to make, aside from logistical issues often involving remote rural communities, and relying on goodwill of communities for participation. As stated by Rogers (1995), different rates of adoption of the improved stove would be expected both within rural communities based on different adopter categories, and between communities based on affluence and exposure to other new technologies. In the case of improved stoves, however, the picture is more complex, because both the pace and degree of adoption need to be considered. As noted by Masera et al. (2000) rather than simply replacing one cooking technology by another, households often rely on multiple combinations of fuels and technologies to meet their cooking needs creating different stove usage groups. Although anecdotal, adoption rates of the improved stove in the current study would tend to support social theories of technology dissemination in that there were participants who adapted to exclusive use of the new technology, participants that partially adopted it but retained the traditional stove either in the same room or elsewhere around the house, participants who required further instructions in the use and maintenance of the stove, and participants who appeared to reject the new technology. Identifying the characteristics of these groups is critical in achieving the maximum benefit from the stove dissemination effort, as the effectiveness of an improved stove dissemination program lies in the numbers adopted, used and maintained, rather than simply the number of stoves disseminated. Not only is this important to maximize the effect of limited funds and manpower for stove dissemination, it is also important in the dissemination process as communication within the community on the performance of the technology is an important aspect in persuading the more cautious adopter groups of the benefits of the new technology.

Reductions in personal exposures and kitchen concentrations

As in many rural communities worldwide, there are a wide variety of stoves, fuels, kitchen constructions and layouts combined with a wide range of family sizes that are prevalent in this region of Mexico, which is hard to capture in a statistically representative manner, without resource prohibitive sample sizes. As monitoring was only conducted in one community for logistical reasons, reductions in $PM_{2.5}$ and CO exposures and kitchen concentrations do not necessarily represent different communities in Michoacan or all possible arrangements in these communities, but rather are indicative of what one might expect with the Patsari stove in similar biomass using communities.

On an aggregate basis, paired comparisons indicated a 35% reduction in median 24-h $PM_{2.5}$ exposure and a 78% reduction in median 24-h CO exposures respectively (Wilcoxon SRT, $n = 26$ $P < 0.001$ and $n = 24$ $P < 0.0001$, respectively). Similarly, paired comparisons of 48-h median kitchen concentrations indicated a 74% reduction in median particulate mass concentrations, and a 77% reduction in median CO concentrations (Wilcoxon SRT, $n = 33$ $P < 0.001$ and $n = 32$ $P < 0.05$, respectively). When stratified by stove usage groups reductions in median 48-hour $PM_{2.5}$ kitchen concentration were 79%, 70% and 68% for homes with exclusive Patsari use, homes using a Patsari and a fogon in the same room, and homes using a Patsari with a fogon in another location, respectively. Similar reductions were observed for median carbon monoxide 48-h kitchen concentrations with 83% and 68% for

Table 4 Ratio of average and median $PM_{2.5}$ and CO personal exposures to kitchen concentrations

	Average			Median		
	Before	After	Difference	Before	After	Difference
Particulate mass (%)						
All stove adoption groups	24	46	22	18	46	28
Exclusive Patsari users	17	28	−11	15	44	−30
Patsari with traditional fogon in kitchen	20	50	−30	19	63	−44
Patsari with traditional fogon in other location	35	44	−9	21	48	−27
Carbon monoxide (%)						
All stove adoption groups	31	33	3	27	26	2
Exclusive Patsari users	17	45	−28	17	46	−29
Patsari with traditional in kitchen fogon	25	45	20	22	15	7
Patsari with traditional fogon in other location	45	15	29	43	26	17

exclusive Patsari users and Patsari users with a fogon inside the kitchen, respectively, and 76% for Patsari users with a fogon in another location.

Percentage reductions in personal exposures were consistently smaller for particulates than they were for CO. While the ratio of CO and particulate matter emissions vary depending on the stage of combustion (smoldering vs. flaming for example) as they are not formed by the same chemical processes in combustion, this is unlikely to be the cause of the different reductions in personal exposure as the kitchen concentrations of both pollutants were reduced by similar percentages. Rather, the difference is likely the result of stratification of smoke in the kitchen as the fraction of personal exposures as a percentage of kitchen concentrations were also greater for CO than for $PM_{2.5}$ during the baseline when homes had traditional stoves (Table 4). As CO is a gas and more mobile it would not be similarly affected.

Although median 48-h $PM_{2.5}$ kitchen concentrations after installation of the improved Patsari stove were somewhat similar for those who were exclusive Patsari users (0.21 mg/m^3) and those who used a Fogon in a different location (0.23 mg/m^3), the decreased percentage reductions in kitchen concentrations for the latter group (68% vs. 79%) were driven by lower initial fogon concentrations. Given that family sizes were similar, the lower initial fogon concentrations suggests either some fundamental difference between households and cooking habits, or that these homes may have already been using a fogon in another location for some cooking tasks. Although percentage reductions of $PM_{2.5}$ concentrations in kitchens that retained a traditional fogon in the same room were high, as expected the resultant median 48-h concentrations (0.30 mg/m^3) were higher than in kitchens of exclusive Patsari users (0.21 mg/m^3) and those who used a fogon in another location (0.23 mg/m^3). Percentage reductions in kitchen concentrations were high for those with a traditional stove in the same kitchen because of relatively infrequent use of the traditional fogon for cooking of nixtamal or water for bathing, although similar reductions in personal exposures were not observed which may indicate a change in behavior.

In addition to reducing central tendency measures of $PM_{2.5}$ kitchen and personal exposure concentrations, installation of the Patsari stove also reduced maximum $PM_{2.5}$ kitchen and personal exposure concentrations in this sample population except for maximum personal exposure when the fogon remained in use in the same room as the Patsari. Similarly, installation of the improved Patsari stove also resulted in decreased maximum CO kitchen and personal exposure concentrations, again with the exception of maximum personal exposure when the fogon remained in use in the same room as the Patsari. Although peak exposures and kitchens concentrations measured in each home were also reduced after installation of the Patsari, more detailed health effect studies would have to be performed to evaluate the health implications of reduction in these peak concentrations.

Prior studies in rural Mexico have demonstrated that typical mean $PM_{2.5}$ kitchen concentrations of 0.887 mg/m^3 with maximum concentrations around 2.0 mg/m^3 for cooking periods depending on type of fuel, stove and ventilation (Brauer, 1998). Mean 48-hour kitchen concentrations for fogons in the current study (0.950 mg/m^3) fall in this range and in the range of comparable studies worldwide (Naeher et al., 2000; range: 0.26–13.80 mg/m^3), but are somewhat lower than those seen in India (Balakrishnan et al., 2002; range: 0.5–2 mg/m^3). After installation of the improved stove the median 24-h kitchen concentrations of $PM_{2.5}$ was still approximately 4 times higher (0.24 mg/m^3) than Mexican Ambient Standards of 0.065 mg/m^3 (SSA, 2005) and 4.5 times the WHO interim standard of 0.075 mg/m^3 as a 24-h mean. Although average 48 hour yard concentrations (0.094 mg/m^3) also exceeded the WHO interim standard, they were not out of the range of what was achievable in reductions given that ambient concentrations at the local health center were below the interim standard (0.059 mg/m^3). For CO previous studies have reported concentrations between 10–500 ppm in kitchens during stove use and 2–50 ppm over 24 h (Von Schirnding et al., 2002). The maximum 48-h CO concentrations were of similar magnitude in homes using the traditional fogon in the current study and 48-h averages ranged from 2 to 22 ppm, with means exceeding 50 ppm during periods when the stove was lit.

As reported by Zuk et al. (2006), patio and ambient $PM_{2.5}$ concentrations were 0.094 and 0.059 mg/m^3 and no significant differences after installation of the improved stove were detected. Patio concentrations appear to show an elevated neighborhood effect from the fugitive emissions of stoves from surrounding homes and from their own (Smith et al., 1994), as 99% of participants reported no burning of trash in the area surrounding their home as additional sources and vehicle traffic in this community is very low. As outdoor sources were similar between the baseline period and post Patsari installation the reductions in particulate and CO concentrations in kitchens do not suffer from bias as a result of large differences in environmental conditions between measurement periods.

None of the women participants in this community consumed tobacco, which is typical of rural communities in this area of Mexico. While some environmental tobacco smoke (ETS) exposure may be present as a result of husbands smoking, the contribution of $PM_{2.5}$ and CO to indoor concentrations from ETS would be extremely small compared to the contribution of the stove for women in these homes. In an evaluation of 400 solid fuel using homes in China as part of a review of the National Improved Stove Program, the effects of smoking on indoor concentrations in the presence of solid fuel burning stoves were not discernable (Edwards et al., 2006a,b). As indoor concentrations in livingrooms were also assessed in the current study and no additional sources of particulates and CO were observed, comparisons of kitchen concentrations and personal exposures were not biased by other large sources of exposure.

In spite of efforts to constrain the variability between homes via household selection criteria, the variability in all groups remained high (Figure 9), where between home variability was approximately double the within home variability for those homes measured over 5 days. Although this variability may be the result of different ventilation status of the homes, which was a significant predictor of indoor levels in India (Smith et al., 2004), we tested only one type of kitchen arrangement, and the semi-continuous records of particulate and CO concentrations suggested that different stove usage patterns may dominate the variability. Questionnaires should therefore focus their efforts exploring this aspect of stove usage.

Relationships of personal exposures to kitchen concentrations

Table 4 shows the ratio of personal exposures to kitchen concentrations before and after installation of the improved stove. As there was an additional stove in another room in the house, or in the yard, that was used for some cooking activities frequently at the same time as the main stove, relationships between kitchen reductions and personal exposure reductions can not be directly derived, although it highlights the the limitations of using indoor concentrations as an estimate of personal exposures. Similar usage of additional stoves and fuels were also observed in China in a review of the National Improved Stove Program (Edwards et al., 2006a,b).

For participants who exclusively adopted a Patsari stove average $PM_{2.5}$ personal exposures were equivalent to 17% of kitchen concentrations for the traditional fogon and 28% after installation of the Patsari in paired comparisons. For participants who maintained a traditional fogon in the same room as the Patsari, however, $PM_{2.5}$ personal exposures were equivalent to 20% of kitchen concentrations for the traditional fogon and 58% after installation of the Patsari in paired comparisons. Thus, the relationship between personal exposures and indoor concentrations not only changed between traditional and improved stove type, but also differed by stove adoption category. Using kitchen concentrations to estimate reductions in personal exposures as a result of installation of an improved stove would therefore result in a bias of 11% and 38% for exclusive patsari users, and those that retained a fogon in the same room, respectively.

Carbon monoxide exposures showed a similar pattern. For those who were exclusive users of a Patsari stove average CO personal exposures were equivalent to 17% of kitchen concentrations for the traditional fogon, and 43% after installation of the improved Patsari. For those who retained a traditional fogon in the kitchen average personal exposures were equivalent to 25% of kitchen concentrations with the traditional fogon, and 45% after installation of the improved Patsari. Thus, for CO using kitchen concentrations to estimate reductions in personal exposures as a result of installation of an improved stove would result in a potential bias of 20% and 26% for exclusive patsari users, and those that retained a fogon in the same room, respectively.

The increase in the ratio of personal exposures to kitchen concentrations after installation of the improved stove may be the result of several factors: (1) the improved Patsari stove may take longer to cook specific food items requiring increased time spent near the stove. There is some evidence of this from stove performance tests (Berrueta et al., 2007), however, more detailed evaluation of this aspect would have to be undertaken using direct observation or other methods such as personal locator transmitters (Allen-Piccolo, unpublished data). Recall time activity diaries in these settings lack the resolution to adequately quantify the differences in time spent in front of the stove. (2) As $PM_{2.5}$ and CO concentrations in indoor environments were reduced, more time may be spent in the kitchen for other reasons. For example, in these 60 homes 93% of families reported eating in the same kitchen where the food was prepared. Although anecdotal some women reported increased use of the kitchen after Patsari installation for children to do homework and play and for themselves to do embroidery.

Although many other studies undertaken around the world, mostly for research purposes, have used indoor measurements to assess the health implications of solid fuel using stoves, few have collected personal exposure samples to assess potential bias in using indoor concentrations as an estimate of personal exposures. Although it has been reported in the US and Europe (e.g. Koistinen et al., 2004; Junlunen et al., 2003), estimating this bias is even more important in rural solid fuel-using households because of strong localized sources and huge spatial and temporal variability in concentrations. Thus, while indoor concentrations under-represent exposures in Finland, in rural Mexican homes kitchen concentrations far exceed personal exposures, and relatively small differences in the time spent in the kitchen may lead to significant differences in personal exposures. Perhaps more importantly, as the ratio of personal exposures to kitchen concentrations varies depending on stove usage group, significant bias can be introduced when associating reductions in $PM_{2.5}$ kitchen concentrations as a proxy for personal exposures with reduced health impacts. This aspect has been little explored in these settings, and is not evaluated as part of most epidemiologic investigations.

A frequently used approach in the US and Europe is to use microenvironment concentrations to reconstruct personal exposures based on time–activity–microenvironment models (Schwab et al., 1990). While this has been used extensively to estimate population-based exposures in the US (McCurdy and Graham, 2003), there are significant drawbacks to these approaches in rural communities in Michoacan, Mexico. In part this is because of the inability of time–activity recall diaries to have sufficient resolution to capture walking in and out of the kitchen, which represents differences in concentration frequently over an order of magnitude over short time periods. It is also due to the large temporal differences in kitchen concentration between when the stoves are lit, which is generally when most time is spent in the kitchen in these rural communities, and when they are not. When this high temporal variability in concentrations is averaged over 24–48 h, which time–activity–microenvironment models weight with the time spent in each microenvironment, the association of time spent in the kitchens when pollution concentrations are highest, and considerably exceed 24–48-h integrated averages, is not captured.

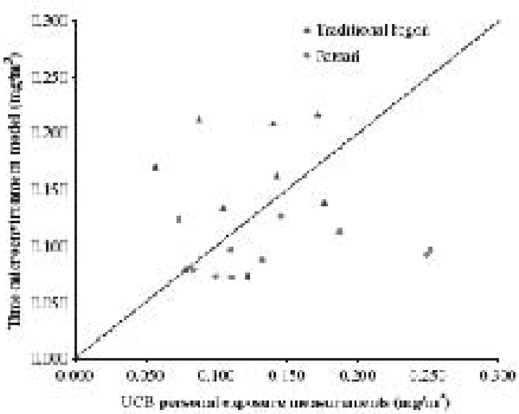

Fig. 10 Relationship between personal exposure measures and time-microenvironment models

Figure 10 shows the correlation between time microenvironment–activity model estimates of personal exposure (Zuk et al., 2006) and measured personal exposures for participants with both estimates, demonstrating how these metrics are not correlated. Perhaps more interesting is the systematic bias in estimation of personal exposures for participants with the traditional fogon compared to those with the improved Patsari stove. Estimates of personal exposure calculated by time activity microenvironment models overestimate measured exposures for participants with the traditional fogon and underestimate exposures with the improved Patsari stove. As there are no other major sources of exposure in these homes, this demonstrates that kitchen concentrations contribute differently to personal exposures before and after installation of the improved stove, which is not captured by the time–microenvironment–activity models. Thus time–microenvironment–activity models should not be used in these rural biomass using households to assess the magnitude of exposures relative to indoor concentrations or exposures or to assess individual exposures in relation to health effects, unless combined with better time–activity estimates such as those proposed using electronic locator transmitters (Allen-Piccolo et al., 2006), which would more accurately capture the contributions of the stove to personal exposures.

Between- and within-home variability associated with length of sampling period

Most epidemiological investigations into the effects of biomass fuel use on exposure estimates rely on grab samples over short periods (usually 24 h). A continuing issue in collecting air pollution samples is what the optimal sampling time would be for collection of samples that minimizes impact on participants (and expense and effort required for monitoring), while achieving maximum benefit in reduction of variability between and within homes. This is not only important for sample size calculations in reducing the number of homes that are needed to show statistically significant differences, it is also important in reducing potential bias in median or mean values used to estimate the effectiveness of the improved stove.

Average within-home variability for the four complete 24-h periods in homes with a traditional fogon ($n = 24$), was 50% of between-home variability (0.22 and 0.44 mg/m^3, respectively). Similarly for homes using the Patsari stove ($n = 10$) the within-home variability was 56% of between-home variability (0.14 and 0.25 mg/m^3, respectively). Thus, in spite of efforts to restrict between-home variability through selecting the housing type, family size, stove location, the overall variability remained high because of individual stove usage patterns, although lower than typical values reported in the literature.

Figure 9 shows reductions in variability associated with monitoring for successive 24-h periods in kitchen environments with the traditional fogon; 60% of the total reduction in the coefficient of variation achieved in kitchen concentrations was achieved after 48 h. Similarly, for $PM_{2.5}$ measurements made in kitchens using the Patsari stove 54% of the total reduction in the coefficient of variation was achieved after 48 h. Although selection of a 48-h sampling period reduced the coefficient of variation by 18% for homes with the traditional fogon and 12% for homes with the improved Patsari stove, the overall variability remained high. While two more days of sampling would have achieved an additional 12% reduction in the coefficient of variation for the traditional fogon and 10% reduction for the Patsari, adding five homes to initial sample resulted in approximately 5–9% decrease in coefficient of variation. Thus, greater benefit would be more likely from an increase in the number of homes sampled rather than increasing the sampling duration given limited time and resources.

Interestingly, extending the sampling period in successive 24-h periods up to 4 days did not substantially change the average estimates of particle concentrations in kitchens in traditional fogon or Patsari homes. A difference of 0.057 mg/m^3 in 48-h average concentrations compared to 4-day average concentrations was observed for homes with traditional fogons compared to 0.011 mg/m^3 for Patsari homes. This would imply a maximum potential bias of 10% in estimates of particulate reductions on an aggregate basis as a result of installation of the Patsari stoves as a result of monitoring for 48 h relative to a 4-day monitoring period. Clearly, similar evaluations would need to be performed during different seasons to assess reductions in long term exposures estimates for health-based assessment, as reductions in air pollution concentrations may differ during the wet season, as a result of changes in ventilation patterns of homes and changes in fuel use. For example, although the dry season in this region of Mexico is prevalent during the majority of the year, however, and reductions seen here would represent the majority of the time, a third of participants in this community reported using the traditional fogon for heating the kitchen during the rainy season.

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CAPÍTULO 3.3.
INDOOR PARTICLE SIZE DISTRIBUTION IN HOMES WITH OPEN FIRES AND IMPROVED PATSARI COOK STOVES

Cynthia Armendáriz*, Rufus Edwards, Michael Johnson, Irma Rosas, Francisco Espinosa, Omar Masera*

(Artículo publicado)

Abstract

La contaminación de partículas por quema de leña en fogones abiertos ha sido extensamente relacionada con efectos adversos a la salud y las concentraciones intramuros se han usado frecuentemente como *proxies* de exposición personal en estudios epidemiológicos. Se asume que la distribución de los tamaños de partículas en fogones abiertos y estufas eficientes de leña no es significativamente diferente. Se midió la distribución de partículas con el impactor de cascada Sioutas en casas usuarias del fogón tradicional y la estufa Patsari en una comunidad rural Purhépecha en Michoacán, México. En promedio las concentraciones en la cocina de partículas menores a 0.25 μm en casas usuarias de fogón se redujeron en 72% con el uso de la estufa Patsari; esto representó una disminución en la contribución de la masa de esta fracción de partículas de 68% a 48% a la masa total de $PM_{2.5}$. Como resultado de esta reducción hubo un aumento de 29% en la mediana del diámetro de masa (MMD, mass median diameter por sus siglas en inglés) en las casas usuarias de estufas Patsari comparadas con aquellas usuarias del fogón tradicional (de 0.42 μm a 0.59 μm, respectivamente). Las concentraciones de exposición personal en casas-fogón representaron el 61% de la concentración en la cocina (156 $\mu g\ m^{-3}$ y 257 $\mu g\ m^{-3}$ respectivamente). En comparación, en las casas usuarias de la estufa Patsari, el valor promedio de exposición personal representó el 77% de la concentración intramuros (78 $\mu g\ m^{-3}$ y 101 $\mu g\ m^{-3}$ respectivamente). Finalmente, si no se toman en cuenta los cambios en la distribución del tamaño de las partículas y en la relación entre exposición personal y la concentración intramuros asociados a la implementación de estufas eficientes, se puede incurrir en una subestimación de los beneficios potenciales a la salud.

* Universidad Nacional Autónoma de México. Corresponding author: Cynthia Armendáriz Arnez; Centro de Investigaciones en Ecosistemas; Universidad Nacional Autónoma de México; cynarar@oikos.unam.mx

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Indoor particle size distributions in homes with open fires and improved Patsari cook stoves[☆]

Cynthia Armendáriz-Arnez[a,1], Rufus D. Edwards[c,*], Michael Johnson[c], Irma A. Rosas[d,3], F. Espinosa[a,2], Omar R. Masera[a,b,1,2]

[a] Centro de Investigaciones en Ecosistemas, Universidad Nacional Autónoma de México, Morelia, Michoacán, Mexico
[b] Centro Interdisciplinario de Tecnología Rural Apropiada, AC, Pátzcuaro, Michoacán, Mexico
[c] Department of Epidemiology, University of California Irvine, Irvine, CA, USA
[d] Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Ciudad Universitaria, Coyoacán 04510, Mexico City, Mexico

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ABSTRACT

Particulate pollution has been clearly linked with adverse health impacts from open fire combustion, and indoor air concentrations are frequently used as a proxy for exposures in health studies. Implicit are the assumptions that the size distributions for the open fire and improved stove are not significantly different, and that the relationship between indoor concentrations and personal exposures is the same between stoves. To evaluate the impact of these assumptions size distributions of particulate matter in indoor air were measured with the Sioutas cascade impactor in homes using open fires and improved Patsari stoves in a rural Purépecha community in Michoacán, Mexico. On average indoor concentrations of particles less than 0.25 μm were 72% reduced in homes with improved Patsari stoves, reflecting a reduced contribution of this size fraction to $PM_{2.5}$ mass concentrations from 68% to 48%. As a result the mass median diameter of indoor $PM_{2.5}$ particulate matter was increased by 29% with the Patsari improved stove compared to the open fire (from 0.42 μm to 0.59 μm respectively). Personal $PM_{2.5}$ exposure concentrations for women in homes using open fires were approximately 81% of indoor concentration levels (136 μg m^{-3} and 257 μg m^{-3} respectively). In contrast personal exposure concentrations were 72% times indoor air concentration levels for women in homes using improved Patsari stoves (73 μg m^{-3} and 101 μg m^{-3} respectively). Thus if indoor air concentrations are used in health and epidemiologic studies significant bias may result if the shift in size distribution and the change in relationship between indoor air concentrations and personal exposure concentrations are not accounted for between different stove types.

1. Introduction

In Mexico 25 million people (nearly one-fourth of total country population and virtually all rural inhabitants) use wood as their main energy source. When burned in simple stoves, like the open fire, the incomplete combustion of wood leads to concentrations of indoor air pollutants usually higher than international WHO air quality standards, and has been implicated as a causal agent of several diseases in developing countries such as acute respiratory infections, chronic obstructive pulmonary disease, lung cancer, tuberculosis, low birth weight and cataracts (Bruce et al., 2000). Among the wide range of pollutants emitted from biomass burning nearly 5% of the carbon released is particulate matter (Andreae et al., 1998; Reid et al., 2005). In residential areas where wood is the predominant source, wood stoves contributed as much as 80% of the ambient fine particle concentrations during winter (McDonald et al., 2000) and this pollutant has been most clearly linked with adverse health impacts. Biomass burning is one of the largest sources of accumulation mode particles globally (Reid et al., 2005); but little is known, however, about the size distributions of particulate air pollution in indoor air generated by biomass burning for energy provision in these rural communities. Even less is known about the changes in the particle size distribution in indoor air that result from installation of improved stoves.

[☆] In this paper we present the differences in particle size distributions in indoor air as a result of biomass burning open fires and improved Patsari stoves in rural homes in Mexico and evaluate the implications for the measured effectiveness of improved stoves.

* Corresponding author. Tel.: [illegible]
E-mail address: [illegible] (R.D. Edwards).
[1] Tel.: [illegible]
[2] Tel.: [illegible]
[3] Tel.: [illegible]

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To date, several studies have suggested a causal relation between exposure to wood smoke particles and adverse health effects (Barregard et al., 2006; Sällsten et al., 2006; Fritche et al., 2006; Koenig et al., 2005; Avakian et al., 2002). Health benefits and effectiveness of improved stoves have traditionally been presented as percentage reductions in indoor air concentrations of particulate matter (McCracken et al., 2007; Naeher et al., 2007) or carbon monoxide as a proxy (Naeher et al., 2007). Combined with age, height, ventilation rates and breathing patterns, the particle size distribution plays a major role in deposition of pollution in different areas of the lung (Kleeman et al., 2000), resulting in adverse health impacts in susceptible populations. In addition to changes in the absolute mass concentration of particulate matter in indoor air, therefore, a shift in the size distribution has major implications for the expression of adverse health impacts, and the potential health benefits of installing improved stoves. Although many studies have reported the absolute reductions in mass concentration of particulate matter (e.g. Chengappa et al., 2007; Dutta et al., 2007; Masera et al., 2007), there are few measurements of size distributions from open fire stoves, and to our knowledge there are no studies that report the change in size distribution in indoor air that results from installation of improved stoves and resultant implications for health benefits of this technology.

In this paper we present the differences in particle size distributions in indoor air as a result of biomass burning open fires and improved Patsari stoves in rural homes in Mexico, and evaluate the implications for the measured effectiveness of improved stoves.

2. Methods

This study was part of the "Patsari Cookstove Program" a multi-institutional collaboration on the design and dissemination of woodburning improved cookstoves and to monitor their environmental, social and health implications. To date 15,000 Patsari cookstoves have been disseminated in several Mexican States. A comprehensive monitoring program of use of Patsari improved cookstoves has documented reductions in indoor air pollutants (Armendáriz Arnez et al., 2008; Zuk et al., 2007), symptoms related with health outcomes (Riojas-Rodriguez et al., 2008; Romieu et al., 2009), greenhouse gas emissions (Johnson et al., 2008), increased energy efficiency and savings in fuelwood consumption (Berrueta et al., 2008), adoption and perceptions (Magallanes, 2006; Pine et al., 2011; Troncoso et al., 2007), fuelwood renewability (Ghilardi et al., 2009) and potential for carbon offsets (Johnson et al., 2009).

2.1. Study site and sampling plan

The study was conducted in Tanaco, an indigenous rural community of 3000 habitants in the state of Michoacán, in central western Mexico, prioritized for the high dependence on biomass for primary energy provision (Ghilardi et al., 2007). About 85% of the population in Tanaco burns wood in open fires for cooking and heating (INEGI, 2001). 10 homes with improved Patsari stoves were randomly selected from a local NGO database of improved Patsari stoves installed in the community and compared to 11 randomly selected homes that used open fires in the community. Personal exposures and indoor air concentrations of particulate matter were assessed over a 24 h period from March to April 2007 during the dry season. Participants also responded to a questionnaire for detailed recall of cooking activities, stove and wood type used during the sampling period. The participants primarily used wood for energy provision, had families of 5–7 members and kitchens enclosed by four walls. Kitchens designs vary but 90% of the homes have wood plank walls separated by gaps with average kitchen size of 4.3 × 3.4 m. Only 5% of homes had walls with many gaps >1 cm between the planks that made up the walls, 42% of the kitchens had walls with many gaps <1 cm, 33% had walls with a few gaps <1 cm, and 19% had solid cemented walls without gaps. Average ambient temperatures were 14.33 °C (8.21 °C min–32.27 °C max) with 48% relative humidity (28.11% min–71.18% max). Participants gave informed consent according to protocols for inclusion of human subjects approved by the institutional review board committee at the University of California at Irvine.

2.2. Stove design

The most common traditional stove is the "U" shape fogon (Fig. 1a) made of clay and cement, which emits particulate air pollution directly into the kitchen with the open side used to add wood to the fire. The brick Patsari cookstove (Fig. 1b) has a closed combustion chamber with a primary and secondary cooking surface or "comal" and a flue venting pollution outside the home. A complete description of the brick Patsari stove can be found in Berrueta et al. (2008). The Patsari cookstoves were disseminated as 1) an affordable local technology, 2) an alternative to mitigate indoor air pollution and health effects and 3) an effective way to save fuel.

2.3. Environmental and personal exposure measurements

Indoor air measurements were standardized at 1.25 m above ground, 1 m distant from the main comal and at least 1.5 m from windows and doors. PM samples were collected using Sioutas

Fig. 1. Stove types included in the study. A) "U" shape fogon and B) Brick Patsari cookstove.

Table 1
PM mass concentration (mg m⁻³) and differences by stove type.

Size bin (μm)	Open fire PM (mg m⁻³)			Patsari PM (mg m⁻³)			% Mass reduction
	median	mean	SD	median	mean	SD	
<0.25	0.121	0.173	0.148	0.037	0.048	0.036	72*
0.25–0.5	0.036	0.039	0.017	0.017	0.020	0.012	48*
0.5–1.0	0.015	0.017	0.008	0.012	0.013	0.007	26
1.0–2.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	27
>2.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	51
$PM_{2.5}$	0.218	0.257*	0.176	0.088	[illegible]	0.052	60*
TSP	0.287	0.317	0.188	[illegible]	0.143	[illegible]	55*

* Significant at $p < 0.05$ level (Student's t-test).

cascade impactors (SKC Inc., USA) equipped with Leland Legacy Pumps (SKC Inc., USA). PM size fractions of >2.5, 2.5–1.0, 1.0–0.5 and 0.5–0.25 μm were deposited on 25 mm, 0.5 μm pore size Teflon filters (SKC Inc., USA) and particles <0.25 μm on 37 mm, 2.0 μm pore size Teflon filters (SKC Inc., USA). Flow rates were measured with a Drycal primary flow meter (Bios International, USA) and set to 9.0 l min⁻¹ for Patsari samples and 4.5 l min⁻¹ for open fire homes and were within ±10% post-sampling period. 4.5 l min⁻¹ was for sampling open fire homes to minimize flow fluctuations from high mass deposition, with impactor inlets reduced to half their size with metallic tape to maintain the same airflow velocities over the deposition filters as those produced using the formerly specified airflow of 9.0 l min⁻¹. Filters were equilibrated for 48 h at 21 ± 2 °C and 40 ± 5% relative humidity before being weighed on an electronic microbalance (Cahn Microbalance Model 29, Thermo Electron Corp., USA). Ten field blank filters were also collected with a mean mass difference of 0.5 μg. Since this was less than 0.2% of the mean particulate mass collected on filters (397 μg) no mass adjustments were made.

UCB Particle Monitors (UCB-PMs) (University of California Berkeley, USA), were co-located with cascade impactors for indoor monitoring and worn at the waist belt of participating women for personal monitoring. The UCB-PM is a semi-continuous (1 min averages) light scattering nephelometer whose photoelectric sensor has demonstrated to be most sensitive to particles with an aerodynamic diameter less than 2.5 μm (Litton et al., 2004). Laboratory validation of UCB-PM response in relation to particle size for monodisperse aerosols and combustion particles has been characterized by Edwards et al. (2006). Field validation of the use of the UCB particle monitor to estimate $PM_{2.5}$ concentrations in biomass burning kitchens has also been reported (Chowdhury et al., 2007). Inter-instrument variability in aerosol sensitivity was accounted for by applying an adjustment factor derived from four controlled co-locations within a cylindrical 1.2-m diameter steel combustion chamber using combustion aerosols generated by combustion of small pieces of local fuel wood collected. The methodology for the chamber testing is presented in detail in Chowdhury et al. (2007).

STATISTICA software was used for all statistical comparisons.

3. Results

Table 1 shows 24 h mean, median and standard deviation of PM mass concentrations in indoor air in 11 homes with open fires and 10 homes with improved Patsari stoves for the 5 size bins of the Sioutas cascade sampler (>2.5 μm, 2.5–1.0 μm, 1.0–0.5 μm, 0.5–0.25 μm, <0.25 μm). The largest fraction of the particulate mass concentration was contributed by the smallest size fraction <0.25 μm for both open fires and improved Patsari stoves. In addition, the largest difference in the size distribution in indoor air between homes with open fires and Patsari improved stoves was in the smallest size fraction where the mass concentration in homes with improved Patsari homes was 72% smaller than that in homes with open fires. For both homes with open fires and improved Patsari stoves the next largest contributor to the PM mass concentration was the largest size fraction of particles >2.5 μm. Tancitaro has unpaved streets with considerable fine dust resulting in high concentrations of resuspended dust. Fig. 2 shows the characteristic differences in color of the largest size fraction, and to some extent the fraction 1–2.5 μm that likely resulted from this resuspended dust. The third largest contributor to the PM mass concentration for both homes with open fires and homes with improved Patsari stoves was the second smallest size fraction 0.25–0.5 μm, which also corresponded to the second largest difference in mass concentration with 48% smaller mass concentration in homes with improved Patsari homes compared to homes with open fires. Although the mass concentrations in size fractions 0.5–1.0 μm and 1.0–2.5 μm were also reduced in homes with improved Patsari stoves, the differences were smaller, and not significant with these sample sizes.

Fig. 3 shows relative contributions of each size fraction to $PM_{2.5}$ and TSP mass concentrations. Significant differences were seen between indoor air concentrations for the open fire and the improved Patsari stove for the smallest size fraction <0.25 μm, which contributed 67% of indoor air $PM_{2.5}$ concentrations for the open fire and 48% for the Patsari, showing a reduced relative contribution of this size fraction of 19% for homes with Patsari stoves relative to open fires. Similarly, the smallest size fraction contributed 55% of indoor air TSP concentrations for the open fire and 34% for the Patsari, showing a reduced relative contribution of 21% for this size fraction. Significant differences were also seen for the 0.25–0.5 μm size fraction which contributed 15% to $PM_{2.5}$ indoor concentrations for the open fire and 20% for the Patsari improved stove, and for the largest size fraction >2.5 μm, which contributed 17% to $PM_{2.5}$ indoor concentrations for the open fire and 26% for the Patsari improved stove. Thus there was a large reduction in the smaller particles in indoor air of homes with improved Patsari stoves and a shift in the distribution to the larger particle size ranges. In summary, therefore, the largest differences in the size distribution between homes with open fires and improved Patsari stoves were for particles less than 0.5 μm as a result of venting the smoke outside the home with a flue by the improved Patsari stove.

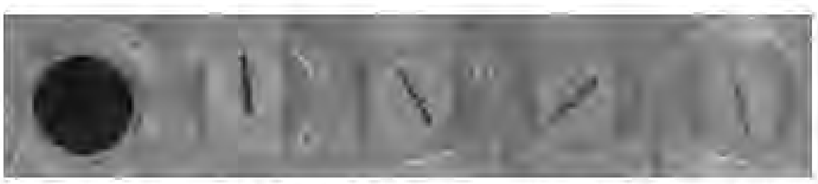

Fig. 2. Filters from Sioutas cascade impactor showing the color change in the large size fractions as a result of resuspended dust from unpaved roads with size fraction from left to right as follows: <0.25 μm, 0.25–0.5 μm, 0.5–1.0 μm, 1.0–2.5 μm, >2.5 μm.

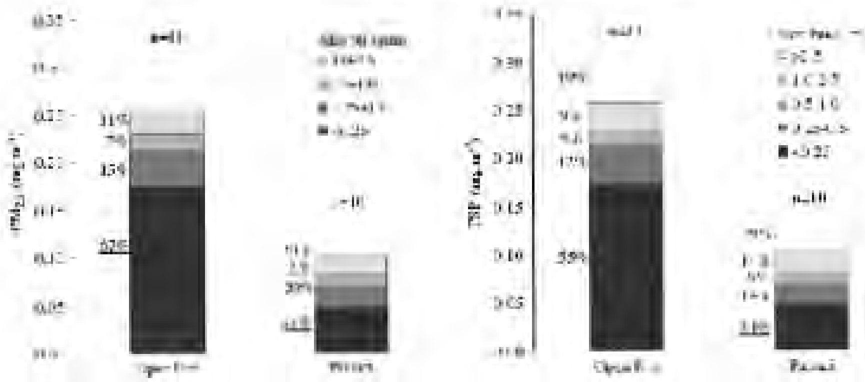

Fig. 3. Relative [illegible] $PM_{2.5}$ [illegible] concentrations in homes with open fires and homes with improved Patsari stoves.

Mean 24-h $PM_{2.5}$ concentrations in homes with improved Patsari stoves were 50% (Student's t-test, $p < 0.01$) lower than homes with open fires (0.101 mg m^{-3} and 0.257 mg m^{-3}, respectively). Similarly, mean personal exposures were 50% (Student's t-test, $p < 0.01$) lower for the primary cooks in homes with improved Patsari stoves compared to primary cooks in homes with open fires (0.78 mg m^{-3} and 0.156 mg m^{-3}, respectively). Fig. 4 shows a comparison of reductions in kitchen concentrations in Tanaco compared to reductions in indoor $PM_{2.5}$ concentrations in a nearby community Comachuén (Armendáriz Arnez et al., 2008). Although the percentage reductions in the two communities differ (50% compared to 67% respectively), the percentage reductions are more influenced by the initial concentrations in the home as the improved stove reduces concentrations consistently across homes.

Table 2 shows the correlation of the light scattering continuous UCB particle monitor with the size fractions measured with the Sioutas cascade impactor in kitchens with open fire and improved Patsari stoves. The light scattering UCB particle monitor correlated best with the size fraction 0.25–0.5 µm for both homes with open fires ($r^2 = 0.85$) and homes with improved Patsari stoves ($r^2 = 0.85$). Subsequently the light scattering monitor correlated best with the smallest size fraction for the open fire as this size fraction contributed the greatest to mass concentrations, but the larger size fractions for the Patsari improved stove, as the larger size fractions have a greater relative contribution to mass concentrations compared to the open fire and light scattering sensor in the UCB is more sensitive to the larger size particles (Edwards et al., 2006; Litton et al., 2004).

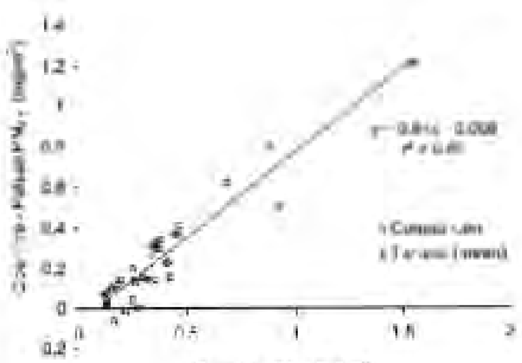

Fig. 4. [illegible] $PM_{2.5}$ mass concentrations in [illegible] homes with open fires and improved Patsari stoves [illegible] compared to before and after measurements [illegible] the same stove type in a nearby community Comachuén.

4. Discussion

Mass median diameter (MMD) of indoor $PM_{2.5}$ particulate matter increased by 30% with the Patsari improved stove compared to the open fire (from 0.24 µm to 0.32 µm, respectively). These findings are comparable to other studies. Venkataraman and Rao (2001) reported unimodal distributions with MMDs of 0.5–0.8 µm across [illegible] stove types for PM emissions from biofuel combustion, and Hu et al. (2007) reported a bimodal distribution with a predominant mode at 0.12–0.32 µm and a smaller mode at 0.76 µm during the whole burning cycle of woody fuels. Although Tanaco has unpaved streets with considerable foot traffic resulting in high concentrations of resuspended dust that had a characteristically different color in the largest size cut of the Sioutas cascade impactor (Fig. 2), over 80% of particle mass concentrations in these indoor environments were submicron consistent with other studies. For example in the simulated village house Smith (1987) found that an open wood burning stove released 85% of total PM mass emissions as submicrometer particles. Reid et al. (2005) reported that approximately 80–90% of the volume of biomass burning particles is in the accumulation mode ($d_p < 1$ µm) and Park and Lee (2003) found that for all biofuel combustion cases, 90% of the mass of PM was between 0.03 and 3.76 µm.

Table 2

[illegible]

PM size fraction (µm)	Open fire		Patsari		Difference in β_1
	β_1 (mg m^{-3} per mm^{-1})	r^2	β_1 (mg m^{-3} per mm^{-1})	r^2	
<0.25	0.026	0.61	0.025	0.36	−1%
0.25–0.5	**0.0037**	**0.85**	**0.014**	**0.96**	**280%**
0.5–1.0	0.0018	0.57	0.0059	0.89	[illegible]
1.0–2.5	0.0018	0.38	0.0059	0.75	[illegible]
>2.5	0.0020	0.35	0.012	0.42	[illegible]
TSP	0.057	0.61	0.056	0.53	78%
PM_{10}	0.035	0.70	0.035	0.67	57%

[illegible]

Johnson et al. (2008) reported that Patsari cookstoves improve combustion efficiency compared to open fires. Although particle size measurements for flaming and smoldering combustion for a moderately sized fire have reported larger particles associated with lower combustion efficiencies (Reid and Hobbs, 1998), direct comparison of the particle size in indoor air and combustion efficiency of the stove cannot be made since the Patsari stove has a flue that vents smoke outside the home, and indoor air concentrations reflect fugitive emissions and re-penetration from outdoors.

Although there was approximately 54% reduction in $PM_{2.5}$ mass concentrations in indoor air in homes with an open fire stove compared to homes with an improved stove, the real difference is in the mass of the fine particle fraction, as other mass fractions are much less reduced. Since the finer particle fractions are those thought to be most associated with adverse health impacts, the potential benefits of improved stoves are underestimated, as there is over 77% reduction in the smaller size fraction. Perhaps more importantly, evaluation of improved stoves on the basis of the $PM_{2.5}$ mass concentration, without consideration for the significant change in particle size distribution (a change in MMD from 0.42 µm to 0.59 µm) would produce biased estimates of the relationship of reductions in $PM_{2.5}$ mass concentrations and expression of health effects relative to studies of urban ambient air health effects, where size distributions are more uniform. In addition since the differences in the size distribution are likely to be technology dependent, and whether the stove has a flue venting to the outdoors, evaluation of the potential benefits of each individual technology are likely to be biased without consideration for changes in the size distribution in indoor air that result.

Since the size distribution is systematically different between homes with open fires and improved Patsari stoves (Fig. 3), and the response of light scattering instruments in relation to mass concentrations is dependent on particle size (Sioutas et al., 2000; Chakrabarti et al., 2004), Table 2 highlights the difference in mass response of light scattering instruments for different stove types, where the slope (β_1) of the relationship between $PM_{2.5}$ mass concentrations and response of the light scattering UCB particle monitor are substantially different between homes with open fires and homes with improved Patsari stoves. Using a mass response coefficient derived for open fires with light scattering monitors would lead to 24% underestimation of mass of indoor air concentrations in homes with the improved Patsari stove due to the differences in the size distribution. Without adjusting for size distribution differences, therefore, would lead to 15% overestimation of the benefits of reductions in indoor air concentrations of $PM_{2.5}$ as a result of installation of improved Patsari stoves. Thus when evaluating the effectiveness of an improved stove intervention using light scattering instruments, especially in relation to epidemiologic studies, any changes in size distribution of particulate matter in indoor air need to be accounted for when relating the response to mass concentrations, or to health impacts.

A greater complication for health studies that use indoor air pollution concentrations is that the relationship between personal exposures and indoor air pollution levels in the kitchen changes significantly for each stove type. For example, on average personal exposure concentrations for women in homes using open fires were approximately 61% of indoor concentration levels. In contrast personal exposure concentrations were 77% of indoor air concentration levels for women in homes using improved Patsari stoves. Personal exposure concentrations with Patsari improved stoves are therefore closer to indoor air pollution levels than with open fires. A likely explanation is the potential greater contribution of other sources to personal exposure concentrations when the contribution from the cookstove has been reduced, as reported in a nearby community by Zuk et al. (2007). Other contributing explanations may be that the women spend more time in the kitchen, or that personal exposure monitors are in closer proximity to fugitive emissions from the improved stove than the indoor air monitors. Riojas-Rodriguez et al. (2008) reported that women in 5 communities including the community in the current study spent 1.5 more hours in the kitchen (from 4 to 5.5) when the improved Patsari stove has been installed.

Although the differences in $PM_{2.5}$ indoor air concentrations between homes with open fires and homes with improved stoves were lower than those measured in a before and after intervention in a nearby community Comachuén with the same improved stove (Armendáriz-Arnez et al., 2008), the difference reflects the lower indoor air concentrations in homes in Tanaco using the open fire rather than a change in performance of the improved stove. Fig. 4 shows that the stove was performing as effectively as in Comachuén when the difference in indoor air concentrations in homes with open fires and Patsaris are plotted against the open fire concentrations for the two communities. Since stoves with flues tend to reduce indoor air concentrations to consistently low concentrations the absolute percentage reduction in indoor air pollution levels tends to be more influenced by the original concentration with the open fire. As a result these results demonstrate that percentage reductions are not the best metric for evaluating the stove performance. Reporting the slope, intercept and standard error of the regression line in Fig. 4 would provide a much more meaningful assessment of consistency in stove performance.

Possible explanations for the lower indoor air concentrations in homes in Tanaco with open fires are that 10 homes do not capture the full range of variability in indoor air pollution levels in homes. In addition 55% of homes in Tanaco elevated the traditional fogón stove onto a table for easier cooking. Since smoke levels tend to be quite stratified in these rural kitchens, this could lead to lower concentrations at the height of the monitors. Other possibilities are the increased use of open fires to heat bathing water outside the kitchen and only 20% of the homes reported nixtamal boiling the day of monitoring. Tortillas, water heating and nixtamal cooking are the most time and wood consuming activities for rural people.

5. Conclusions

The Patsari improved stove results in significantly changes in the particle size distribution in indoor air compared to the open fire. On average the Patsari improved stove resulted in 72% ($p = 0.03$) reduction in indoor concentrations of particles less than 0.25 µm, reflecting reduced contributions of this size fraction to $PM_{2.5}$ mass concentrations from 68% to 48% (Wilcoxon sign rank test $p = 0.03$). As a result the mass median diameter of indoor $PM_{2.5}$ particulate matter was increased by 20% with the Patsari improved stove compared to the open fire (from 0.35 µm to 0.42 µm, respectively).

Significant bias may result in health and epidemiologic studies if the shift in size distribution and the change in relationship between indoor air concentrations and personal exposure concentrations are not accounted for between different stove types.

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CAPÍTULO 3.4
CHANGES IN POLYCYCLIC AROMATIC HYDROCARBON CONCENTRATIONS AS A RESULT OF THE INSTALLATION OF IMPROVED PATSARI COOK STOVES IN MEXICO

Cynthia Armendáriz Arnez[1], Rufus D. Edwards[4], Zhihua Fan[6], Michael Johnson[3], Irma A. Rosas[5], Francisco J. Espinosa[1], Victor Berrueta[2] Omar R. Masera[1 2]

[1]Center for Ecosystems Research, National Autonomous University of Mexico, Antigua Carretera a Patzcuaro No. 8701, Colonia Ex-Hacienda de San José de la Huerta, Morelia, Michoacán, Mexico, 58190, Tel. 5255-5623-2709.

[2]Interdisciplinary Group of Appropriate Rural Technology, A.C., Centro Comercial El Parian, Int. 17 Patzcuaro, Michoacan, Mexico, 61609, tel. +5243-4342-3216.

[3]Department of Environmental Health, Science, and Policy, College of Health Sciences, Room 258, 101 Theory Suite 250, University of California at Irvine, CA, 92697-3957.

[4]Department of Epidemiology, University of California Irvine, 101 Theory, Suite 250, room 258, Irvine CA 92697-3957

[5]Centro de Ciencias de la Atmósfera, National Autonomous University of Mexico, Ciudad Universitaria, Coyoacan, 04510, Mexico City, Mexico, Tel. 5622

[6] Environmental and Occupational Health Sciences Institute, University of Medicine and Dentistry of New Jersey – Robert Wood Johnson Medical School and Rutgers University; 170 Frelinghuysen Road, Piscataway, New Jersey 08854.

Contact Information: Rufus Edwards tel. 949 824 4731.

E-mail: edwards@uci.edu

Abstract

El objetivo de este studio fue evaluar el impacto de la implementación de estufas eficientes de leña Patsari respecto a la contaminación intramuros y los valores de exposición personal de hidrocarburos aromáticos policíclicos (PAHs) resultado de la combustión de leña en viviendas rurales mexicanas. Se midió la concentración en la cocina y la exposición personal a 8 compuestos encontrados en fase gaseosa (naftaleno, acenaftileno, acenafteno, fluoreno, fenantreno, fluoranteno, antraceno y pireno) en 21 hogares, 10 usuarias del fogón tradicional y 11 usuarias de la estufa Patsari. Se encontraron reducciones de entre el 50 y 80% en la concentración promedio individual de los PAHs asociados al uso de estufas eficientes mientras que se reportaron reducciones de entre el 20 y el 74% en los valores de exposición personal. La importancia relativa de cada PAH estuvo fuertemente influenciada por el tipo de estufa cambiando así la relación entre exposición personal-concentración en cocina. El potencial cancerígeno para el total de PAHs es extremadamente alto comparado con otros estudios en ambientes urbanos. Finalmente si estas concentraciones son típicas de nuestra realidad rural en México, alrededor de la cuarta parte de la población se encuentra expuesta crónicamente a niveles de contaminación intramuros que exceden por mucho los límites establecidos en Europa y que se sabe, tienen efectos perjudiciales en la salud. Si se utilizan las concentraciones intramuros como proxies de la reducción en los valores de exposición personal puede incurrirse en errores al subestimar los beneficios de una intervención como es la implementación de una estufa mejorada.

Abstract

The aim of this study was to investigate the impact of domestic Patsari improved cook-stoves on polycyclic aromatic hydrocarbons (PAH) indoor concentrations and estimates of personal exposure from wood burning in rural Mexican homes. Kitchen and personal gas concentrations of eight individual PAH compounds (naphtalene, acenaphthylene, acenaphtene, fluorene , phenanthrene, fluoranthene, anthracene and pyrene) were measured in 21 homes, 11 users of Patsari improved cookstove and 10 users of traditional fogon. Reductions of ~50% to 80% in PAH individual mean concentrations associated with the use of Patsari stoves were obtained, while reductions of ~20% to 74% were obtained for personal exposure estimates. The relative importance of each PAH is strongly affected by the type of stove changing the personal exposure-kitchen concentration ratio. The cancer potency for total PAH was extremely higher compared to other urban environment studies. Finally if these remained concentrations are typical of rural conditions in Mexico, nearly one fourth of the population is chronically exposed to enormous levels of indoor air pollutants fairly higher than European guidelines found to be harmful to human health. Errors could be feasible if the reductions in kitchen pollutant concentrations are taken as proxies for personal exposure reductions.

Introduction

In Mexico, nearly 25 million people rely in biomass for cooking and heating. Domestic wood burning in open fires releases a dense smoke that contains a wide range of toxic pollutants such as particulate matter and organic compounds including polycyclic aromatic hydrocarbons. These compounds emitted indoor and outdoor are cause of intensive research due to its environmental and health implications (Johnson et al., 2008; Smith et al., 2006). Inhalation exposure to PAHs may cause adverse human health effects such as respiratory diseases including cancer (Boström et al., 2002). The International Agency for Research on Cancer (IARC) classified indoor emissions from domestic biomass burning as probably carcinogenic to humans. There are not estimations of PAH emissions released from incomplete combustion in Mexico but in Sweden 280 tonnes annually constitute the inventory of wood burning for residential heating, higher than emissions from traffic (Gustafson et al, 2008).

Benzo(a)pyrene (BaP), the most widely investigated PAH has been classified as carcinogenic to humans and the lung cancer risk from inhalation exposure to a PAH mixture can be estimated by adding individual PAH concentrations using the toxicity equivalency factors (TEFs); the cancer potency of each PAH is calculated on the basis of its BaP equivalent concentration (Böstrom et al., 2002).

Few studies have evaluated the impact of residential biomass burning on indoor air pollution levels; much less studies have published the impact of improved cook stoves as an alternative to mitigate PAH indoor concentrations and health outcomes.

Methods

Study Site

The study was conducted in Tanaco, an indigenous rural community of 3,000 habitants located in the state of Michoacan, in central western Mexico. It has been identified as one of the highest priority counties due to the impacts of wood consumption within the region (Ghilardi et al, 2007). About 85% of the population in Tanaco burns wood in open fires for cooking and heating (INEGI, 2001). The participants fulfilled certain features for being included in the survey: exclusive users of wood or low gas consumption, families of 5-7 members and kitchens enclosed by four walls. Kitchens designs vary but 90% of the homes have wood plank walls separated by gaps and size average of 4.3 x 3.4 m. Ventilation was estimated using a 4 criteria scale, being 0 none ventilated (walls without gaps), 1 little ventilation (walls with some gaps < 1 cm), 2 normal ventilation (walls with many gaps < 1 cm between the planks) and 3 Completely ventilated (walls with many gaps > 1 cm). An analysis of frequency shows that 43% of the kitchens have normal ventilation, 33% have little ventilation, 19% have none ventilation and only 5% have walls with many gaps > 1 cm. Kitchen is a place where the family spend 4-6 hours since they use to get together after the journey. Children often do their homework inside of the kitchen while the lady is cooking or cleaning. Pine and oak are the most common wood species used in Tanaco, they use them indistinctly although cookers prefer oak since they reported "*burns slowly, embers remains burning longer and less smoke is* *released from combustion*".

Stove design

The most common traditional stove is the "U" shape fogon (Fig. 1) that allows the distribution of combustion by-products inside of the kitchen and the open side is used to add wood to the fire. These were replaced by brick Patsari cookstoves (Fig. 1) which have a close combustion chamber and a flue venting outside the home. A complete description of the brick Patsari stove can be found in Berrueta et al 2008. The Patsari cookstoves were disseminated as 1) an affordable local technology, 2) an alternative to mitigate indoor air pollution and health effects and 3) an effective way to save fuel and diminish forest pressure. People from Tanaco didn't have to pay for the stove since they participated in the different monitoring surveys and received it for free although this was an exceptional situation.

Sampling Plan

From March to April 2007, 21 homes were measured during the dry season, 11 open fire and 10 Patsari homes. The houses were selected according to a local NGO database of constructed and used stoves. For fogon houses, people were invited to participate. All signed a consent form according to protocols of inclusion of human subjects and consent procedures approved by Institutional review board Committee at the University of California at Irvine and participating institutes. The sampling design included 2 different tests: 1) PAH and PM concentrations near the stove (standardized at 1.25 m above ground, 1 m distant from the main *comal* and at least 1.5 m from windows and doors) and 2) PAH and PM personal exposure. Equipment was installed in the morning and picked it up the next day after a period of 24 hours measurements. A cooking questionnaire was applied to have a detailed recall of cooking activities, stove and wood type.

Environmental and personal exposure measurements

Eight PAH were considered for this study: phenanthrene, fluorene, naphtalene, acenaphtene, fluoranthene, pyrene, anthracene and acenaphthylene. Fan-Lioy passive PAH samplers (FL-PPS) were located near the stove; for personal exposure the FL-PPS was tied up to the waist cooker. The FL-PPS consists of two components, one sampler holder and 4 adsorption units constructed from 80 sections of a 1 cm long gas chromatography capillary column, designed as a minihoneycomb denuder type diffusive sampler. For detailed FL-PPS laboratory and in-field tests see Fan et al (2006). Ten field and ten laboratory blanks were included to control for field contamination and lab manipulation but since the difference was less than 1 µg, it was not necessary adjustment for the mass difference. Filters were weighed at 19.5ºC and 39.5 relative humidity conditions.

STATISTICA and R software was used to process all data.

Results

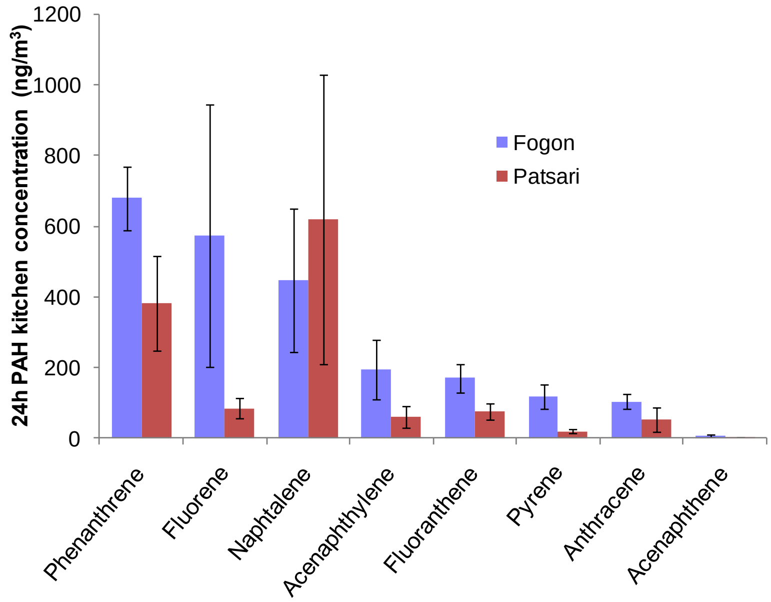

Fig. 6. 24-h PAH kitchen concentrations for fogon and Patsari users

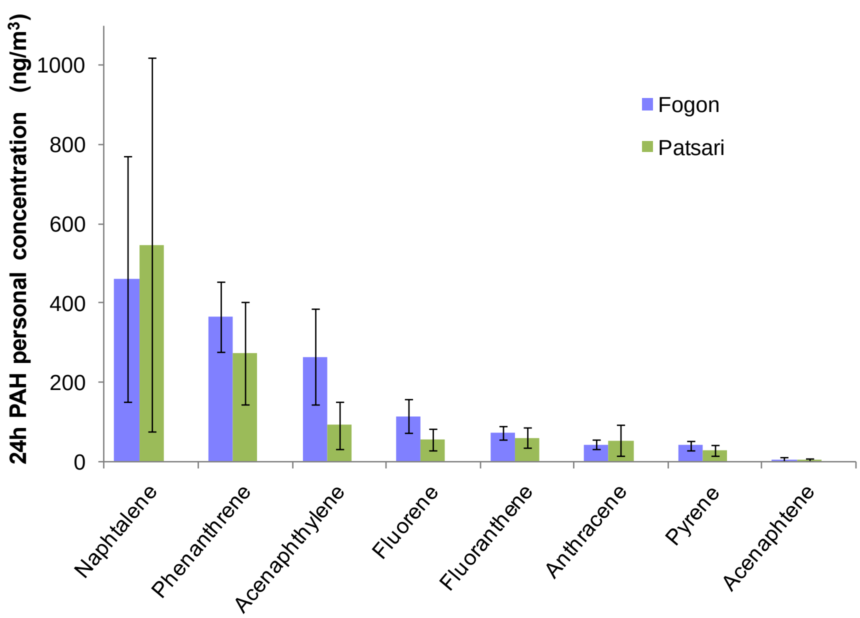

Fig. 7. 24-h PAH personal exposure concentrations for fogon and Patsari users

Tabla 1 24-h Averages, median and máximum values of PAHs in fogón and Patsari homes.

comp abv	fogon				Patsari				Mann-Whitney U test	% change
	mean	median	s.d.	max	mean	median	s.d.	max	P-value	Median
kitchen										
Nap	447	109	678	2,134	619	58	1,299	4,207	0.57	46
Acy	195	48	281	797	60	16	98	319	0.31	66
Ace	7	0	13	45	2	0	6	18	n.a.	n.a.
Fl	573	192	1,237	4,275	85	54	85	264	0.03*	72
Phe	680	551	301	1,172	383	197	423	1,301	0.03*	64
Ant	103	113	69	215	51	19	109	359	0.04*	83
Flu	171	137	134	526	74	56	75	267	0.02*	59
Pyr	118	84	111	416	19	18	17	47	0.001*	79
SUM	***2,293***	***1,234***		***9,580***	***1,295***	***418***		***6,783***		***66***
personal										
Nap	460	76	981	3,182	548	41	1,315	4,235	0.82	45
Acy	265	103	387	1,229	92	26	138	420	0.23	74
Ace	6	0	13	38	4	0	8	25	n.a.	n.a.
Fl	115	85	135	465	55	48	45	155	0.23	44
Phe	365	374	282	948	273	271	190	730	0.50	28
Ant	44	42	39	125	54	25	101	339	0.55	41
Flu	72	83	53	170	60	64	29	111	0.71	22
Pyr	41	39	36	110	28	33	18	52	0.60	17
SUM	***1,367***	***802***		***6,267***	***1,114***	***507***		***6,068***		***37***

All concentrations are reported as ng/m^3. b.* values are significant at P<0.05. c. compounds abvreviations corresponds to naphthalene (Nap), acenaphthylene (Acy), acenaphtene (Ace), Fluorene (Fl), phenenatrene (Phe), anthracene (Ant), Fluoranthene (Flu) and Pyrene (Pyr).d. A multivariate non parametric test in R program showed a positive effect from the stove when the 8 variables were compared. In a refined analysis statistical difference were obtained for Fluorene, Floranthene and Pyrene.

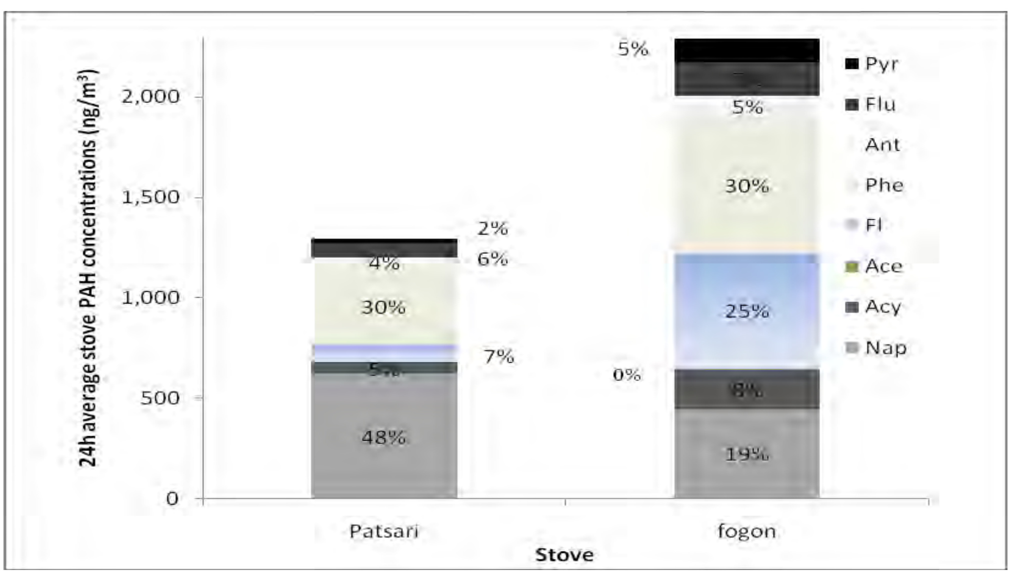

Fig. 8. Relative contribution of individual PAHs

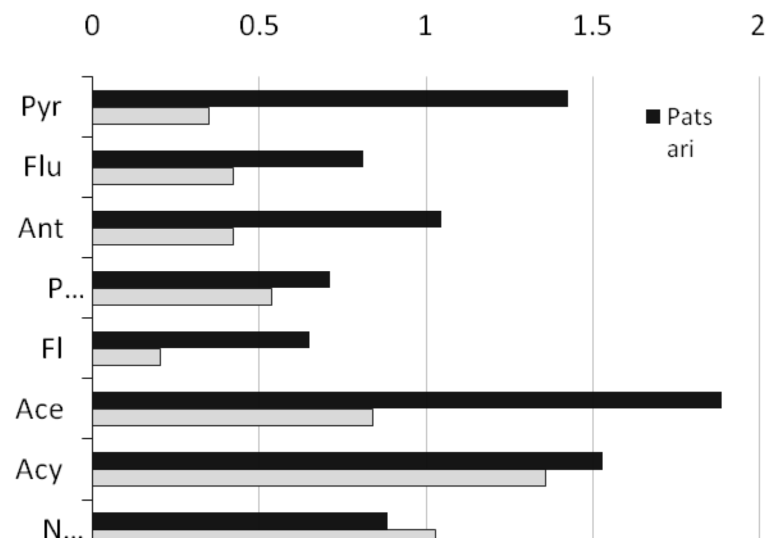

Fig. 9.Personal to kitchen ratio for fogon and Patsari homes

Tabla 2 Cancer potency of each PAH on the basis of its benzo[a]pyrene equivalent concentration

		Patsari		fogon	
Comp	**TEF[bd]**	**Mean[a]**	**BaP_{equiv}[c]**	**Mean[a]**	**BaP_{equiv}**
Nap	0.001	619	0.62	447	0.45
Acy	0.001	60	0.06	195	0.19
Ace	0.001	2	0.00	7	0.01
Fl	0.001	85	0.08	573	0.57
Phe	0.001	383	0.38	680	0.68
Ant	0.01	51	0.51	103	1.03
Flu	0.001	74	0.07	171	0.17
Pyr	0.001	19	0.02	118	0.12
Σ		**1,295**	**2**	**2,293**	**3**

a. All concentrations are in ng/m^3, b. TEF: Toxic Equivalent Factor, c. BaP_{equiv}: Equivalents of benzo [a] pyrene, d. Data from Nisbet and LaGoy (1992).

Kitchen concentrations. Gustafson et al (2008) reported that the gaseous phase accounted for over the 90% of 3-ring PAHs and 77-88% of the 4-ring PAHs for wood burning homes in Sweden, so the sum of all individual measured PAHs in this study was used as a proxy of the potential total concentration of exposure, hereafter total PAHs. Tabla 1 shows 24-h averages, median, standard deviation and maximum peaks of 8 PAH concentrations in the kitchen of 11 homes using traditional fogon and 10 homes of Patsari users. Average 24-h kitchen total PAHs concentration for women using the traditional fogon was 2,293 ng/m^3. Fig. 6 shows a paired distribution of individual PAH kitchen concentrations for homes using fogon and for those that adopted Patsari stove. All individual PAHs kitchen concentrations were higher for homes using the traditional fogon except naphthalene. Phenanthrene, fluorene and naphthalene represented the highest concentrations of individual PAH followed by Acy, Flu, Pyr and Ant. for fogon and Patsari homes. The average concentrations of individual PAHs ranged from 7 ng/m^3 (Acenaphthene) to 680 ng/m^3 (phenanthrene) for homes with fogon and from 2 ng/m^3 (acenaphthene) to 619 ng/m^3 (naphthalene) for homes with Patsari stove (Tabla 1). The detection limit reported for individual PAH (estimated as 3 times the standard deviation of the field blanks) (Fan et al., 2006) range from 0.1(ANT) to 6.3 ng/m^3 (NAP). The lowest individual PAH average concentration was the acenaphthene compound (2-7 ng/m^3), value that falls in the limit of quantification (LOQ). The highest average concentration measured was the phenanthrene reaching 680 ng/m^3 for homes using fogon. Maximum peaks of 4,275 ng/m^3 (Fluoerene) and 4,207 ng/m^3 (naphthalene) were found for homes using fogon and Patsari respectively. Moreover maximum peaks of total PAH concentrations of 9,580 ng/m^3 and 6,783 ng/m^3 for homes using fogon and Patsari respectively were found. A non-parametric multivariate analysis in R program was run to test the effect of the stove in PAH concentrations. Values of Tmax (0.03), Tsum (0.01), and TssT2 (0.02) showed a positive effect when perform the combined test and significant differences for fluorene, fluoranthene and pyrene were found (see annex 7 for a detailed R script, run and results). Tabla 1 shows the reductions associated with the use of Patsari stoves. For the paired fogon and Patsari comparison, median 24-h kitchen total PAHs concentrations were 1,234 ng/m^3 for women with fogon and 418 ng/m^3 for women with Patsari stoves. This represents a 66% reduction in median total PAH kitchen concentrations. Significant reductions in Fl (72%, $P < 0.03$), Phe (64%, $P < 0.03$), Ant (83%, $P < 0.04$), Flu (59%, $P < 0.02$) and Pyr (79%, $P < 0.001$) were found. Although high percent reductions for Nap and Acy were obtained (46% and 66%) for paired fogon and Patsari comparison, no statistically differences were detected. The lack of statistically significance for comparisons between traditional fogon and Patsari stoves reflects the low sample numbers (n=10); in opposition of kitchen median reductions, the variability in PAH individual concentrations was increased for Patsari users.

Personal exposures. Average 24-h personal exposure total PAHs concentration for women using the traditional fogon was 1,367 ng/m^3 (Tabla 1). The paired fogon-Patsari distribution of individual PAH personal concentrations showed higher medians for homes using fogon compared with Patsaris.

Averages reflects the same pattern except for Nap and Ant. Naphtalene, phenanthrene and Acenaphthylene represent the highest individual PAHs concentrations and fluorene, Fluoranthene, Anthracene and Pyrene, the lowest. Concentration of Acenaphtene was below the LOQ. Average concentration of individual PAHs ranged from 6 ng/m^3 (Ace) to 460 ng/m^3 (Nap) for homes using the traditional fogon and 4 ng/m^3 (Ace) to 548 ng/m^3 (Nap) for homes using Patsari. The highest average concentration was the naphtelene, reaching 548 ng/m^3 in homes using Patsari stove. Maximum peaks of 4,235 ng/m^3 (Nap) and 730 ng/m^3 (Phe) were measured for Patsari stove users. For fogon users maximum peaks of 3,182 ng/m^3 (Nap) and 1,229 ng/m^3 (Acy) were found. Interestingly maximum concentrations of exposure of 6,267 ng/m^3 and 6,068 ng/m^3 could be found in the homes using traditional fogon and Patsari respectively, during the monitoring period.The Non-parametric multivariate analysis in R program didn't show any effect of the stove for personal exposure PAH individual concentrations. Tabla 1 shows the reductions associated with the use of Patsari stoves. Although PAH personal exposure concentrations in all individual compounds were reduced in homes with improved Patsari stoves (Fig. 7), they were not significant with this sample sizes. Personal exposure total PAH concentration was reduced in 37%, from 802 ng/m^3 to 507 ng/m^3. Individual PAH reductions fluctuate in the range of 17% (Pyr) to 74% (Acy).

Relative contribution of individual PAH. Fig. 8 shows the relative contributions of individual PAH to total concentration. Significant differences between kitchen PAH concentrations for the traditional fogon and Patsari stove homes were seen for Fluorene, phenanthrene, Anthracene, Fluoranthene and Pyrene which contributed 67% in indoor air PAH total concentrations for the fogons and 49% for the Patsari, showing a reduced relative contribution of 18% for homes with Patsari improved cook stove relative to traditional fogon. In the same way, for homes using the traditional fogon, Phenanthrene, Fluorene and Naphtelene contributed with 30%, 25% and 19% of total average PAH concentration respectively, which represents 74% of the total amount reached during the monitoring period. Naphtelene and phenanthrene constituted the 78% of total PAH concentration for Patsari users (Fig. 8). The contribution of the rest compounds to total PAH concentration was less than 10% each accounting for less than 25% of total PAH concentration in both fogon and Patsari homes. Naphtelene and fluorene show clear differences between their contributions to total PAH concentration. For homes using fogon Nap and Flu contributed with 19% and 25% and for Patsari users their contribution shifted significantly to 48% and 7%.

Personal exposure to kitchen ratio. Fig. 9 shows personal exposure to kitchen PAH concentration ratios. For all PAH compounds, the personal exposure to kitchen concentrations ratio for Patsari users were higher than for traditional fogon users, except for naphtelene. For Patsari users, pyrene, anthracene, acenaphtene and acenaphthylene, personal exposure concentrations were higher than kitchen concentrations. For homes with traditional fogon, all PAH personal exposure concentrations were lower than kitchen concentrations, except naphtelene and acenaphthylene. For fogon users, personal exposure concentrations of 5 PAH compounds (fluorene, phenenthrene, anthracene, fluoranthene and pyrene) were 50% of kitchen concentrations or below but for Patsari users, personal exposure concentrations for all PAH compounds were 60% of kitchen concentrations or higher.

Importance of individual PAH compounds for total cancer risk. To assess the toxicity of individual PAH compounds in the mixture, we estimated the cancer potency of each PAH (expressed as equivalents of benzo[a]pyrene [BaP_{equiv}]) using the toxic equivalent factor [TEF] developed by Nisbet and LaGoy (1992) and the mean indoor concentrations (Tabla 2). The sum of carcinogenic PAHs (ΣPAH) measured in Patsari homes were lower (2 BaP_{equiv}) than for traditional fogon homes (3 BaP_{equiv}). For both Patsari users and traditional fogon homes the main contributors to ΣPAH were naphtelene with 0.62 and 0.45 of BaP_{equiv} and Anthracene with 0.51 and 1.03 of BaP_{equiv} respectively. Naphtelene, fluoranthene, phenanthrene and anthracene accounted for 91% and 85% of ΣPAH of BaP_{equiv} for Patsari and fogon homes. Anthracene contributed with 4% and 5% to total PAH mean concentrations but with 29% and 32% of ΣPAH of BaP_{equiv} for Patsari and fogon homes respectively.

Discussion

Kitchen concentrations. In this study, concentrations of 8 PAH compounds were measured in rural kitchens in Michoacan, Mexico where the use of biomass for cooking and heating is a common practice. Concentrations of personal exposure were estimated as well. The composition of a mixture of PAH emitted to the air are influenced by multiple factors such as type of fuel and combustion technology. Several studies have reported that residential burning of wood is the largest source of anthropogenic PAHs (Ramdhal et al, 1982) Boström et al (2002) reported that domestic wood burning and road traffic are the major sources of PAH in Sweden.

There have been several improved stove dissemination projects in Mexico since 1980, but a few formal in-field evaluations of the effectiveness of the strategy in reducing levels and exposure to indoor pollutants, including PAHs. Mean 24-h levels of some individual PAHs found in this study (fluorene, phenanthrene, anthracene, fluoranthene and pyrene) are 2 to 3 orders of magnitude higher than other published concentrations in urban industrial environments (Ohura et al., 2004). Significant reduction of 66% in total PAH kitchen concentrations for Patsari users demonstrated that the stove could be an effective alternative to reduce indoor air pollutants although effects of re-penetration and leakage from the stove have not been evaluated. Unfortunately, there are not clear stated PAHs air quality guidelines for rural environments and there is a lack of health implications knowledge toward individual or a mixture PAH levels of exposure so current standards are not an effective protecting threshold and potential benefits of improved stoves dissemination programs could be underestimated.

Indoor 24-h total PAH mean level of 2,293 ng/m^3 was found for fogon homes and the use of Patsari stove showed a significant reduction of 66% (1,295 ng/m^3, $P < 0.05$) in total PAH median concentration in the kitchen. Total PAH concentrations estimated here are difficult to compare with other studies since the number and the species may differ but it results remarkable that rural homes in Michoacan could reached concentrations of 2,293 ng/m^3 for only gas phase PAHs not including particle bounded compounds. Notwithstanding the differences in number and species of PAH measured in other studies, total mean PAHs concentrations in rural fogon and Patsari homes included in this monitoring survey, resulted 2 to 6 fold higher than the range of 20-164 ng/m^3 found in Manchester (Coleman et al., 1997), 48.3 to 548 ng/m^3 in Chicago (Simcik et al., 1997). Individual PAH reductions for kitchen concentrations associated with the use of Patsari stove in the range of 46% to 83% were obtained but concentrations still remain 1 to 2 orders of magnitude higher than urban published studies (Gustafson et al., 2008, Ohura et al., 2004). Other studies have reported average concentrations of 0.94 ng/m^3, 12 ng/m^3, 13 ng/m^3, 31 ng/m^3, 2.9 ng/m^3 and 1.9 ng/m^3 for individual PAH (anthracene, acenaphtene, fluorene, phenanthrene, fluoranthene and pyrene respectively) in homes near an industrial area in Shimizu, Japan (Ohura et al, 2004). These concentrations are about 50 times slower that the ones reported in this survey (103 ng/m^3, 7 ng/m^3, 573 ng/m^3, 680 ng/m^3, 171 ng/m^3 and 118 ng/m^3) for the same PAH compounds in traditional fogon homes. Indoor average levels of some individual PAH in reference homes with traditional fogon were significantly higher (about 2 to 6 fold) compared with homes with improved Patsari stoves. Reductions of PAHs indoors showed that the installation and use of Patsari improved cook stoves constitutes an alternative to mitigate indoor air pollution and personal exposure for women that spent an average of 4 h in the kitchen. This results are in the same direction as other studies, for example García-Frapolli et al (2010) estimated that the fuel savings and health impacts (reductions in indoor air pollution and exposure) are the main contributors to economic benefits constituting 53% and 28% of the overall benefits in a cost-benefit analysis of Patsari improved cook stove program in rural Mexico. Other publications have given evidence of the reductions in indoor air pollutants, fuel savings and emissions associated with the implementation and use of a new improved cook stove in rural communities (Smith et al., 2010; Bruce N et al, 2004, Berrueta et al, 2007, Johnson et al 2007, Armendáriz-Arnez et al, 2008) but an integrated evaluation of the performance of the stoves is still missing.

Personal exposure reduction. Human exposure usually occurs to PAH mixtures rather than to individual compounds. On an aggregated basis, paired comparisons indicated a 37% reduction in median 24-h total PAH concentration; reduction in estimates for personal exposure were lower than for kitchen concentrations. Use of Patsari improved cook-stoves reduced all median individual PAH personal exposure estimates and almost all maximum peaks of concentrations (except naphthalene and anthracene). A drastic significant reduction (79%, $P<0.001$) in pyrene (stated as carcinogenic by IARC) concentration in the kitchen was observed in contrast with 17% of reduction for personal exposure naphthalene concentration; these may be a clear indicator of changes in combustion conditions. Since the distribution of the gas phase individual PAHs in the mixture indoors changed significantly for fogon and Patsari homes, this should be considered for future epidemiologic in-field evaluations due to the enormous health implications associated with PAH exposure. It has been demonstrated that variability in individual stove usage patterns is high for rural homes (Armendariz-Arnez et al., 2008). Not significant differences for personal exposure individual PAH estimates were found; one possible explanation is the sample size used for the statistical analysis for fogon and Patsari homes ($n=11$ and $n=10$, respectively). Even when mean total PAH estimate of exposure was reduced with use of Patsari cook-stove, a total PAH concentration of 1,114 ng/m^3 still prevailed. These concentrations fairly exceed personal exposure studies of nonoccupational cohorts which reported total PAH concentrations in the range of 1.09 to 24.7 ng/m^3 (Sisovic et al., 1996, Zmirou et al., 2000) while match with other occupational exposure studies where concentrations were much higher ranging from 1.3 to 397 µg/m^3 being the highest exposure for asphalt paving workers in California (Angerer et al., 1997, Watts et al., 1998, Van Delft et al., 1998, Pyy et al., 1997).

Relative contribution of individual PAHs. Phenanthrene, fluorene and naphthalene represented the highest mean concentrations of individual PAHs accounting for 74% and 84% of total PAH mean concentration for fogon and Patsari homes respectively, followed by acenaphthylene, fluoranthene, pyrene and anthracene which accounted for 26% and 16% of total PAH concentration for fogon and Patsari users respectively. These findings differed with Gustafson et al (2008) where phenanthrene, anthracene, fluoranthene and pyrene constituted up to 79% and 86% of the total PAH concentration in wood burning and reference homes respectively. Bi et al. (2003) reported that fluorene, phenanthrene and their methylated derivatives, fluoranthene and pyrene were the dominant PAH species in the vapor phase for urban atmosphere in Guangzhou, China. Naphtelene was the most abundant PAH in fogon and Patsari personal exposure samples. This is in agreement with Ohura et al (2004) samples, where naphtelene was the highest contributor to total PAH indoor and outdoor concentrations. Mothballs are often used in rural environments in Mexico to heal ear ache, to removed moisture and as a moth repellent so it is feasible that the presence of mothballs indoors influenced kitchen concentrations and personal exposures. Concentrations of naphtelene for traditional fogon homes were similar (447 ng/m^3 in the kitchen vs 460 ng/m^3 for personal exposure) so it is possible that naphthalene exposure occurs from a different source in addition to the stove (i.e. a room used for embroidery for example). Phenanthrene and its methylated derivatives were the most abundant 3-ring PAH in Ohura et al (2004) findings. This is in agreement with our results where phenanthrene was the most abundant PAH compound in kitchen and personal exposure concentrations after naphthalene for fogon and Patsari homes.

PAHs are semi-volatile organic pollutants that occur in both particulate and gaseous phases. The vapor-particle partition have a marked dependence on molecular weight It has been demonstrated that low molecular weight PAHs tend to be highly distributed in gas phase while high molecular weight ones are often associated with particulate matter (Bi et al., 2003). Over 80% of particle mass concentrations in these indoor environments are submicron and since mass median diameter of indoor particulate matter increased with Patsari improved stoves compared to fogons (from 0.59 μm to 0.42 μm) (Armendáriz-Arnez et al., 2010) further investigations are needed to determine the distribution of PAHs particle bounded and its contribution to total PAHs concentrations and exposure.

Personal exposure to kitchen ratio. This research project pretends that its findings figure as an indicative of what one might expect with the use of Patsari cookstove in similar biomass dependent communities in rural Mexico. Personal exposures reductions were consistently smaller than they were for kitchen concentrations although the ratio between them showed a strong influence of stove type. Fig. 9 shows the personal-kitchen ratio for fogon and Patsari homes. All personal/kitchen ratios for Patsari homes were higher than for fogon homes, except naphtelene. For Patsari users, personal exposure estimates were generally higher than kitchen concentrations for 4 of the 8 measured PAHs (Pyrene, anthracene, acenaphthylene and acenaphtene) while in fogon homes for most of the PAHs (6 from a total of 8 compounds) personal concentrations represented between 30-60% of kitchen concentrations. It is possible that once the Patsari cook-stove is installed and the woman learns how to clean and give proper maintenance to the stove, she spends more time in the kitchen and could be exposed to leakage smoke indoors or since the chimney releases smoke outdoors, it is feasible that the woman could be exposed to PAH dry deposition process when she is doing some embroidery labor. Furthermore since a multiple use of different technologies is a common practice in rural Mexico, it is possible that these homes may have already been using a fogon in another location for some specific cooking tasks increasing smoke emissions and exposure. For fogon homes, the personal exposure concentrations were higher than the kitchen only for acenaphthylene and naphtelene. Future studies should be accompanied with recall of detailed time-activity diaries. Finally it has been demonstrated that fundamental differences between house-holds and cooking habits exist and this should be considered when the complex emission reality is trying to be explained. Important health implications could be understated from these personal exposure-kitchen ratios.

Importance of individual PAH compounds for total cancer risk. The WHO recommended a unit risk used to express the concentration in the air that theoretically would lead to lifetime cancer risks of $1x10^{-4}$, $1x10^{-5}$ or $1x10^{-6}$. Then each country has to decide which risk level would be acceptable for them. If we consider $1x10^{-5}$ as a conservative approach, then the WHO risk value would lead to a guideline of 0.1 ng/m^3 B[a]P as an indicator of the PAH mixture. The sum of carcinogenic PAHs (ΣPAH) means measured for fogon homes were clearly higher than for Patsari users. The sum of ΣPAH of BaP_{equiv} was slightly higher for fogon homes compared to patsari users. The values of ΣPAH of BaP_{equiv} are fairly higher than Gustafson et al. (2008) findings for indoor levels of PAH in homes with and without wood burning in Sweden but are comparable to Ohura et al. (2004) results who measured indoor and outdoor levels of PAH in Shimizu, Japan, where the sum of ΣPAH of BaP_{equiv} for summer and winter was 1.78 and 1.7 respectively.

Four individual PAHs (naphthalene, fluoranthene, phenanthrene and anthracene) accounted for over 85% of ΣPAH of BaP_{equiv} which suggest that low molecular PAH -although are not significant carcinogens- should be taken into account when assessing the health impact of PAH mixtures. Further research should evaluate the role of each PAH individual compound (particle and vapor phases) in the carcinogenicity of total PAH.

Fluoranthene has been proposed as an indicator because of his high concentrations and carcinogenicity. The guideline value proposed is 2 ng/m^3. In our study (for kitchen concentrations) this value was exceeded about 80 times in the fogon houses and at least 30 times in Patsari homes.

Even when most individual PAH concentrations were reduced with the use of Patsari improved cook sotve, the levels are still fairly higher than existing BaP and fluoranthene health-based guidelines values.

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CAPÍTULO 4
DISCUSIÓN GENERAL Y CONCLUSIONES

Se han realizado numerosos estudios para documentar el impacto de las estufas en relación con la CI (Zuk et al, 2006), efectos en la salud (Romieu et al, 2009), gases de efecto invernadero (Johnson et al, 2008), adopción (Troncoso et al, 2007), impactos económicos (García-Frapolli et al 2010, ver anexo 2), eficiencia energética y consumo de leña (Berrueta et al, 2008), acceso a la leña (Ghilardi et al, 2009), etc. Es importante contribuir al entendimiento y las repercusiones que una estrategia de intervención tecnológica con una política de ejecución a nivel nacional puede tener antes de decidir sobre el modelo y las condiciones de implementación; de esta forma reducimos el riesgo de enfrentar bajos niveles de adopción y "garantizamos" que el dispositivo a instalar cumpla con los indicadores mínimos de desempeño y buen funcionamiento.

Los costos asociados a una mala decisión en materia de EE, pueden ser muy altos. García-Frapolli et al (2010) reportaron que la Secretaría de Salud gastó alrededor de 787 dólares por vivienda rural en servicios médicos (cantidad per capita para el Estado de Michoacán considerando 6 miembros en la familia) y cerca de la tercera parte fue para atención de enfermedades respiratorias agudas. Al adoptar la estufa, esta cantidad se redujo a 171 dólares. El reemplazo de fogones abiertos por EE repercute en beneficios económicos significativos.

Al inicio de este proyecto, se plantearon varias preguntas de investigación en relación con las concentraciones de algunos contaminantes intramuros por combustión de leña y cuál es el impacto que una intervención tecnológica como las estufas eficientes de leña podría tener en la reducción de estas emisiones al interior de las cocinas así como en la exposición personal de las usuarias. Estas preguntas nos permitieron abordar el estudio con diferentes niveles de análisis; a continuación se discuten los resultados de cada una de ellas así como posibles recomendaciones:

1. ¿Cuáles son los niveles intramuros y de exposición diarios a $PM_{2.5}$ y CO a los que están sujetas las mujeres y niños cuando usan fogones abiertos o EE?

En las comunidades de estudio se encontró un patrón de uso múltiple de combustibles y estufas en concordancia con otros estudios publicados (Zuk et al., 2006; Naeher et al., 2001, Troncoso, 2010). La estufa más usada en la meseta Purhépecha es el fogón en forma de herradura o "U", hecho de piedras, cemento o barro con varillas de metal colocadas encima como sostén del comal u ollas. El lado abierto del fogón se utiliza para "alimentarlo" con leña y las emisiones se distribuyen libremente al interior de la cocina.

La estufa Patsari es una alternativa tecnológica al fogón desarrollada para satisfacer las necesidades de cocción de las viviendas rurales como estrategia para mitigar los impactos de la contaminación intramuros a la salud de las usuarias por la exposición al humo generado por el proceso de combustión. Sus características son que posee una cámara de combustión cerrada que conduce las emisiones al exterior de la cocina a través de una chimenea, tiene un comal de metal, su diseño permite una distribución homogénea del calor en la superficie del comal, se "alimenta" por una entrada pequeña, disminuye el consumo de leña (Berrueta et al., 2007, Berrueta et al., 2008), reduce las emisiones de gases de efecto invernadero (Johnson et al., 2008) y mantiene limpia la cocina.

La población de Comachuén, donde se realizó el primer muestreo, es una comunidad que depende en un 98% de fogones y leña para cocinar, su mayoría son indígenas; la muestra seleccionada constó de 60 casas cuyas características incluyeron cocinas cerradas con cuatro paredes, no compartidas por otros habitantes de la casa y familias de 5 a 9 miembros para controlar lo más posible, los patrones de cocinado, cantidad de leña consumida y tiempo de uso de la estufa.

Una de las dificultades más importantes del muestreo en campo fue la disponibilidad y condiciones de las casas para la segunda etapa; de las 60 casas seleccionadas para caracterizar las reducciones en la exposición personal de las usuarias y en las concentraciones de la cocina en relación con los patrones de uso de las estufas, sólo 34 quedaron disponibles; las otros 26 salieron del estudio por diversas razones (capítulo V).

A pesar de los numerosos problemas de medir la CI en condiciones reales en campo, se confirmaron niveles muy altos de $PM_{2.5}$ en la cocina, encontrándose una concentración promedio de 1.27 mg/m^3 (n=60) y picos máximos de concentración de 4.23 mg/m^3 (n=33) con el uso del fogón. Estas concentraciones concuerdan con otros estudios publicados (Balakrishnan et al, 2002, See et al, 2006, Romieu et al, 2009, Riojas-Rodríguez et al, 2001). Pérez Padilla et al (2010) reportaron picos máximos de concentración de 20-80 mg/m^3 cuando los fogones están prendidos; esto constituye aproximadamente la mitad de la exposición de estas mujeres cocineras. Las concentraciones intramuros en las casas usuarias del fogón de este estudio son aproximadamente 18 veces más altas que el nivel máximo permitido por la Norma Oficial Mexicana para $PM_{2.5}$ en ambientes exteriores (65 µm/m^3) y más altas que los resultados publicados en otros estudios en México (Saatkamp et al, 2000, Riojas-Rodríguez et al, 2001). VonSchirndig et al (2002) publicaron que en numerosos estudios de países en vías de desarrollo, las concentraciones estándar exceden regularmente hasta en 50 veces los niveles máximos permitidos. Ezzati et al (2000) encontraron concentraciones de 50,000 μg/m^3 en la zona inmediata al fuego en Kenya, bajando drásticamente conforme aumentaba la distancia.

El promedio 24 hrs de las concentraciones de exposición personal para usuarias de fogón fue de 0.29 mg/m^3 (n=60) para $PM_{2.5}$ y 2.35 ppm para CO (n=60). Nuestro resultados son similares a los de Zuk et al (2006), quienes encontraron concentraciones de $PM_{2.5}$ de exposición personal de 0.21 mg/m^3 para usuarias de fogón y 0.11 mg/m^3 después de la instalación de la estufa Patsari. La instalación de la estufa modifica los patrones de comportamiento ya que según estimaciones de Zuk et al (2006), hubo una reducción de la contribución de la concentración de la cocina a la exposición personal total de las mujeres (ver Anexo 1). Aunque las concentraciones intramuros y la exposición personal de las usuarias de leña se redujeron significativamente, es necesario plantear futuros estudios para analizar el efecto de la chimenea en los niveles de contaminación extramuros.

2.¿Cuáles son los niveles de reducción en las concentraciones de partículas y monóxido de carbono al interior de las cocinas por el uso de EE de leña?

Se estratificó la muestra para hacer el análisis post-intervención, en grupos, en función del tipo de estufa utilizada y su ubicación. De esta forma, se hizo una clasificación de 3 grupos: i) usuarias exclusivas de Patsari, ii) usuarias de Patsari y fogón en la misma cocina y iii) usuarias de Patsari y fogón en diferente ubicación. En general la Patsari redujo consistentemente las concentraciones intramuros de $PM_{2.5}$ y CO y los niveles más significativos de reducción los obtuvieron las casas con concentraciones iniciales altas. Desde la perspectiva de contaminación intramuros, el uso múltiple de combustibles y/o estufas complica las condiciones experimentales de muestreo pero representa la realidad más común del medio rural.

Al hacer el análisis agregado (con la muestra total, n=33) hubo una reducción de 74% ($p<0.001$) en la concentración de $PM_{2.5}$ asociada a la estufa, a pesar de las diferencias en los patrones de uso de la estufa, que redundó a su vez en una diferencia en las medianas de 0.67 mg/m^3 (0.91 mg/m^3 con fogón a 0.24 mg/m^3 con la Patsari) (n=33). Aunque las reducciones son muy significativas tanto estadísticamente como en términos de reducción de impactos a la salud y gases de efecto invernadero (Romieu et al, 2009; Johnson et al, 2007), las concentraciones promedio alcanzadas con la EE son todavía 3 veces más altas que los niveles máximos permitidos (SSA, 1995). En el análisis estratificado, las usuarias exclusivas de Patsari presentaron una reducción de 79% en la concentración de $PM_{2.5}$ mientras que las usuarias de Patsari - fogón en la misma cocina y el grupo de usuarias Patsari - fogón en diferente ubicación obtuvieron reducciones similares (70% -68%, $p<0.01$). Las reducciones encontradas en este estudio son similares a las que se han publicado en otros estudios como resultado de la implementación de una nueva tecnología para cocción en Guatemala (Naeher et al, 2000; Naeher et al, 2001).

Respecto al CO, en el análisis agregado la reducción en la estufa fue del 77% ($p<0.05$), lo cual representó una diferencia de 6.6 ppm en la concentración promedio (8.6 ppm con fogón a 2 ppm con Patsari). En el análisis estratificado se encontraron las siguientes reducciones: para las usuarias exclusivas de Patsari (83%, $p<0.04$), usuarias de Patsari – fogón en la misma cocina (68%, $p<0.01$) y para usuarias de Patsari – fogón en diferente ubicación (76%, $p<0.07$). Naeher et al (2000) reportaron concentraciones promedio similares a las encontradas en este estudio; por ejemplo para usuarias de fogones abiertos se obtuvo una media de 23 ppm y hubo una reducción del 50% para las usuarias de la estufa eficiente "plancha".

En cuanto a concentraciones 24 h de $PM_{2.5}$ de exposición personal, se encontró una reducción del 35% ($p<0.001$) en el análisis agregado (n=26), de 0.17 mg/m3 a 0.11 mg/m3; los resultados del análisis estratificado mostraron que las usuarias exclusivas de Patsari redujeron en un 38% ($p<0.04$), las de Patsari – fogón en la misma cocina un 2% (NS) y las usuarias de Patsari – fogón en la misma ubicación un 27% (NS).

Se obtuvieron concentraciones promedio de exposición personal de CO de 2.35 ppm (n=60). En el análisis agregado (n=24) se obtuvieron concentraciones 24h de 2.3 ppm con el uso del fogón y 0.5 ppm con Patsari; esto refleja una reducción del 78% ($p<0.0001$) en la exposición diaria de las mujeres que pasan en promedio 4 horas al día en la cocina. En el análisis estratificado las usuarias exclusivas de Patsari redujeron en un 54% (NS) su exposición a CO, las usuarias de Patsari-fogón en la cocina un 78% ($p<0.07$) y las que usaron Patsari-fogón en diferente ubicación un 86% (NS). La tendencia, al igual que en la exposición a $PM_{2.5}$, muestra que las usuarias que decidieron mantener la Patsari y el fogón en la misma ubicación, obtuvieron concentraciones máximas similares a las encontradas antes de la instalación de la EE; en cambio, las concentraciones máximas de exposición de las usuarias de Patsari – fogón en diferente ubicación, se redujeron drásticamente con la instalación de la EE.

Las reducciones de las concentraciones de exposición personal fueron consistentemente menores para $PM_{2.5}$ en comparación con las que se obtuvieron de CO. La tasa de emisiones de contaminantes varía en función de la etapa de combustión aunque esta no parece ser la causa de esta diferencia en las reducciones de $PM_{2.5}$ y CO. Una hipótesis es la estratificación del humo en la cocina; la distribución del CO al ser un gas de bajo peso molecular, móvil, puede verse fácilmente alterado por otros contaminantes de mayor peso, por el aire y por las condiciones de combustión. Este comportamiento se confirma con la fracción de exposición personal y la concentración en la cocina, mayor para CO y menor para $PM_{2.5}$ durante el muestreo basal con fogones tradicionales.

Aunque la reducción de la concentración de $PM_{2.5}$ en la cocina para el grupo de usuarias que mantuvo la Patsari y el fogón en la misma ubicación fue significativa (70%), la mediana de este grupo de usuarias resultó ser mayor (0.30 mg/m^3) que las usuarias exclusivas de Patsari (0.21 mg/m^3) y las que decidieron mantener el fogón en diferente ubicación a la Patsari (0.23 mg/m^3). Esta tendencia podría deberse a que el fogón mantenido en la cocina se haya usado para la preparación del nixtamal o para calentar agua para el baño; sin embargo el patrón de las concentraciones de exposición personal no es similar y no refleja un cambio en los patrones habituales de comportamiento.

Además de la reducción en las medidas de tendencia central de las concentraciones de $PM_{2.5}$ de la cocina y de exposición personal, la instalación de la estufa también redujo los picos máximos de concentración con excepción de la exposición personal de las usuarias que mantuvieron el fogón en combinación con la Patsari en la misma cocina. Esta misma tendencia se observa para las concentraciones de CO. Es necesario documentar con otro tipo de estudios el efecto de la reducción de estos picos de concentración en la salud de los usuarios de leña.

Otros estudios en México han documentado concentraciones medias típicas de 0.887 mg/m^3 en la cocina con concentraciones máximas de 2 mg/m^3 durante los periodos de cocinado dependiendo del tipo de combustible, estufa y ventilación (Brauer, 1998). Las concentraciones de $PM_{2.5}$ con el uso del fogón obtenidas en este estudio son comparables con otras publicadas mundialmente (Naeher et al, 2000 rango: 0.26-13.80 mg/m^3). Con la instalación de las Patsari, se obtuvo una mediana de 0.24 mg/m^3, concentración 4 veces mayor a los estándares ambientales mexicanos (0.065 mg/m3, SSA, 2005) y 4.5 veces mayores a las permitidas por la OMS (0.075 mg/m^3). Las concentraciones medidas en la plaza central de la comunidad mostraron 0.059 mg/m^3, en correspondencia con lo reportado por Zuk et al (2006), donde las concentraciones del patio y el ambiente fueron de 0.094 y 0.059 mg/m^3 y no se observaron diferencias significativas con la instalación de las estufas Patsari. Al sacar el humo de la cocina a través de la chimenea se observa un efecto a nivel de localidad que puede deberse a las emisiones fugitivas de las estufas circundantes y las propias, ya que el 99% de los participantes reportan no quemar basura cerca de sus casas y el tráfico de vehículos es muy bajo. El hecho de que las concentraciones ambientales en la plaza central y en el patio se mantuvieran constantes antes y después de la intervención, muestra claramente que no hay sesgo en las mediciones tomadas durante la realización del estudio.

Uno de los factores más importantes en los estudios de monitoreo en condiciones reales, es la variabilidad entre casas que en nuestro caso, fue el doble de la variabilidad al interior de las casas medidas por 5 días. Aunque un estudio en la India (Smith et al, 2004) reporta que la ventilación es un factor que puede predecir el nivel de contaminación intramuros, en este caso tratamos de controlar esta variable y creemos que las diferencias se deben principalmente a los diferentes patrones de uso de las estufas. Sería recomendable usar las entrevistas o cuestionarios para explorar los aspectos relacionados con el uso.

3.¿Cuál es la relación que existe entre la concentración promedio de $PM_{2.5}$ y monóxido de carbono dentro de las cocinas donde se usan las Patsari? 4. ¿Cuál es la relación entre las concentraciones de exposición personal y la concentración de la cocina?

El análisis de la ocurrencia de picos máximos de concentraciones de $PM_{2.5}$ y CO muestra una correlación significativa tanto para el muestreo con fogón como para el de Patsari (R=0.75 y R=0.62); este resultado concuerda con otros publicados (Naeher et al., 2001) en estudios de contaminación intramuros por combustión de leña. No hay una correspondencia exacta de las concentraciones promedio de los contaminantes pues se producen en diferentes niveles durante los sub-procesos de combustión (flaming "etapa de flama intensa" y smoldering "que arde lentamente"), por lo que la relación entre contaminantes en intervalos cortos de tiempo no es exacta; sin embargo en promedios de 48 h se observa una correlación significativa (62% con datos de fogón y 75% con Patsari). Existe mucha discusión de si la emisión de CO está estrechamente relacionada con la concentración de partículas y aunque algunos autores han encontrado correlación entre los niveles de los dos contaminantes (Naeher et al, 2001), el proceso de combustión depende de numerosos factores por lo que es difícil llegar a una conclusión inapelable.

Los estudios de monitoreo en campo enfrentan la difícil decisión de cuánto tiempo es necesario medir para considerar los resultados representativos de lo que en realidad sucede. Para este proyecto, se midieron las concentraciones de $PM_{2.5}$ con monitores semi-continuos por 5 días (se consideraron 4 periodos completos de 24 h), con el objeto de comparar la variabilidad en los datos. El resultado fue una reducción del coeficiente de variación (COV) de 0.68 a 0.48 en el promedio 24h de la concentración de $PM_{2.5}$ en el fogón. El 60% de la reducción en el COV se dio en las primeras 48 hrs. El análisis de los coeficientes de variación refleja que es mejor aumentar la cantidad de casas al inicio del muestreo que aumentar los días para disminuir la variabilidad. Se debe garantizar por un lado, el minimizar el impacto a las participantes, la cantidad de recursos destinados a la logística y al monitoreo y al mismo tiempo reducir la variabilidad al interior y entre las casas.

Uno de los resultados más importantes de este estudio es la relación entre las concentraciones $PM_{2.5}$ de exposición personal y de la cocina antes y después de la instalación de las estufas Patsari. Al haber un uso múltiple de estufas y combustibles, se pone de manifiesto la limitación de usar las concentraciones intramuros como estimaciones de la exposición personal. Las reducciones asociadas con la cocina y con la exposición personal no mostraron correlación porque dependen de múltiples factores como el tipo y número de estufas, las condiciones de combustión, el tipo y la humedad de leña, la distribución de la mezcla de contaminantes, la ventilación, el tiempo de permanencia en los diferentes lugares, etc…

Para usuarias exclusivas de Patsari la exposición personal de $PM_{2.5}$ equivale al 17% de la concentración en la cocina cuando se usa el fogón y al 28% con la Patsari. Para aquellas usuarias que mantuvieron el fogón y la Patsari en la cocina, este cociente de exposición personal-concentración en la cocina es de 20% con fogón y 58% con la instalación de la Patsari; por lo tanto la relación entre exposición y concentración en la cocina cambia dependiendo del tipo de estufa pero también dependiendo del grupo o categoría de adopción. El estimar la exposición personal usando la concentración en la cocina puede implicar un error de entre el 11 y el 38% para usuarias exclusivas de Patsari o usuarias de Patsari-fogón en la cocina, respectivamente.

El aumento en el cociente (exposición personal respecto a la concentración de $PM_{2.5}$ y CO en la cocina) antes y después de la instalación de la Patsari, puede deberse a varios factores: que la estufa necesite más tiempo para cocinar ciertos platillos, aumentando por lo tanto el tiempo de permanencia frente a la estufa o que al haber una reducción en las concentraciones intramuros de $PM_{2.5}$ y CO la usuaria pase más tiempo dentro de la cocina realizando otras labores como el bordado o la supervisión de la tarea de los niños. Entonces, las concentraciones intramuros no son representativas de los niveles de exposición personal y en el medio rural de nuestro país las primeras exceden significativamente las segundas, sin embargo pequeñas diferencias en el tiempo de permanencia en la cocina puede representar diferencias significativas en la exposición de las mujeres usuarias de leña.

Los resultados del apartado 3.3 corroboran que la exposición personal a las concentraciones de $PM_{2.5}$ de usuarias Patsari es más cercana a la concentración de la cocina que la exposición personal de usuarias del fogón; esto se refleja en los resultados: 77% para Patsaris y 61% para fogón. Esto puede deberse a varias razones, entre ellas la contribución de otras posibles fuentes externas a la exposición personal cuando la contribución de la estufa se ha reducido; que la usuaria de la estufa pase mayor tiempo en la cocina o que los monitores personales estuvieron más cerca de las emisiones fugitivas de la estufa Patsari en comparación con los monitores intramuros.

Hay una tendencia generalizada en Europa y Estados Unidos a predecir la exposición personal con modelos microambientales de tiempo-actividad. Esta metodología puede resultar completamente inadecuada para las comunidades rurales de nuestro país por las dificultades y fallas que provee la información de los diarios de tiempo-actividad; en primer lugar, las participantes de este tipo de estudios tienen una percepción del tiempo diferente a nosotros, por lo que la información proporcionada no corresponde con la realidad, pero si se logra obtener la información de los diarios, éstos cuentan con una resolución limitada para capturar minuciosamente los patrones de encendido de la estufa y cocinado así como la entrada y salida de las cocinas. Otro problema son las diferencias temporales de las concentraciones de la cocina cuando la estufa está prendida o apagada. Normalmente los modelos microambientales de tiempo-actividad utilizan el promedio de la variabilidad de las concentraciones en 24h o 48h y asignan un peso al tiempo permanecido en los diferentes microambientes, pero no logran capturar la asociación del tiempo permanecido en la cocina y de la exposición cuando la concentración de contaminantes es muy alta. Zuk et al (2006) mencionan las dificultades a las que se enfrentaron para estimar los niveles de exposición personal a partir de concentraciones microambientales y diarios de tiempo-actividad, los supuestos en los que se basaron y las limitaciones de sus estimaciones. Los resultados de este estudio mostraron que los modelos de tiempo-actividad subestimaron las concentraciones de exposición personal cuando se usaron fogones y sobre estimaron cuando se realizó el monitoreo con el uso de Patsaris; por esta razón no deben usarse estos modelos para predecir exposición a menos que se tengan dispositivos de localización electrónicos que provean información precisa y certera.

5.¿Existen diferencias en la distribución del tamaño de las partículas en función del tipo de estufa utilizada?

En los estudios de contaminación intramuros por combustión de leña, por lo general se asume que la distribución de tamaños de las partículas es igual para la combustión del fogón y de las EE y que la relación entre la concentración de la cocina y las de exposición personal son las mismas para ambas estufas. Pero esto no es así, este estudio muestra claramente que la distribución de los tamaños de partículas es dependiente del tipo de estufa y se debe considerar el efecto de la chimenea de la estufa al conducir las emisiones al exterior si se quiere hacer una estimación correcta de los beneficios potenciales de una intervención tecnológica como es la implementación y uso de la estufa Patsari. Johnson et al (2008) demostró que las estufas Patsari mejoran la eficiencia de combustión en comparación de los fogones. Aunque algunos estudios de fuegos han reportado la asociación de partículas de gran tamaño con bajas eficiencias de combustión (Reid y Hobbs, 1998) no se pueden hacer comparaciones directas de los tamaños de partículas intramuros y la eficiencia de combustión de la estufa por las particularidades inherentes a la estufa, como la chimenea que hace un efecto de “tiro” y succión y conduce las emisiones hacia el exterior; por otro lado las concentraciones intramuros provienen de emisiones fugitivas y partículas de re-penetración del exterior.

Los resultados del análisis de tamaños muestran claramente que la contribución más grande a la masa total de las partículas medidas proviene de la fracción más pequeña (0.25 µm) y que la reducción más grande en la concentración intramuros (72%) al hacer la comparación entre fogón y Patsari proviene de esta misma fracción. La segunda fracción en importancia respecto a la masa total de partículas es PM>2.5 µm, que incluyó el polvo re-suspendido que se depositó en los filtros de muestreo; la concentración de la masa de partículas de esta fracción para usuarias de Patsari fue un 31% menor que las usuarias del fogón. La siguiente fracción en orden de importancia fue la de PM 0.25-0.5 µm, tanto en usuarias de fogón como en Patsari; la concentración de masa de esta fracción presentó una reducción del 48% en la comparación de fogón y Patsari. Las concentraciones de PM de las fracciones de PM 0.5-1 µm y 1.0-2.5 µm presentaron reducciones (26 y 27%) aunque no fueron significativas.

En el análisis de la contribución relativa de cada fracción a la masa total de $PM_{2.5}$ se obtuvo que la fracción más pequeña contribuye en la mayor proporción tanto para fogón (67%) como para Patsari (48%) aunque hay una diferencia clara de 19% entre las dos contribuciones. De forma similar, la fracción de PM<0.25 contribuyó con el 55 y 34% de la masa total de partículas suspendidas totales (TSP) para fogón y Patsari respectivamente mostrando una diferencia de 21% entre las dos contribuciones. Tomando en cuenta la distribución y contribución de todas las fracciones medidas, los resultados muestran una reducción significativa de las partículas más pequeñas en las concentraciones de la cocina al comparar fogones con Patsaris y un cambio en la distribución de los rangos de partículas más grandes.; en resumen las diferencias más grandes en la distribución de tamaños de partículas entre las casas con fogones y Patsaris fueron para las fracciones menores a 0.5 µm, con la estrategia de conducir el humo hacia el exterior de la cocina a través de la chimenea.

Como consecuencia del cambio en la distribución de fracciones de partículas, el diámetro de la mediana de la masa (MMD) aumentó un 29% con la Patsari (de 0.59 µm a 0.42 µm). Esto coincide con otras publicaciones. A pesar de que Tanaco, la comunidad donde se realizó el estudio, es una localidad que no cuenta con calles pavimentadas y la resuspensión de polvo es visible en el transcurso del día, el 80% de la concentración en masa provino de partículas sub-micrométricas, lo cual es consistente con otros estudios. Reid et al (2005) reportó que entre el 80 y 90% del volumen de las partículas procedentes de la combustión de biomasa tienen un diámetro menor a 1 µm. Aunque en este estudio hubo una reducción del 50% en la concentración de masa total de $PM_{2.5}$ en la comparación antes y después de la estufa, la mayor reducción corresponde a la disminución en la concentración de las fracciones de partículas finas ya que las otras fracciones presentaron reducciones menores. Resulta imprescindible mencionar que las partículas más finas son las que más se han asociados con perjuicios en la salud de los pobladores por lo que los beneficios de una intervención tecnológica como la estufa Patsari se podrían estar subestimando al no tener en cuenta los cambios en la distribución de los tamaños de las partículas emitidas, en nuestro caso, la fracción de PM<0.25 µm, fue la que obtuvo la mayor reducción en concentración (72%). Probablemente más importante aún es que por lo general los estudios de contaminación intramuros reportan beneficios asociados a la reducción en las concentraciones de $PM_{2.5}$ y relacionan ésta disminución con efectos a la salud, sobre todo en estudios de ambientes urbanos donde las distribuciones de tamaños son más uniformes.

Al haberse demostrado que la distribución de tamaños de partícula es dependiente del tipo de estufa y a su vez como la respuesta de los monitores de dispersión de luz (como el monitor de registro semi-continuo UCB utilizado en este estudio) respecto a la masa total de partículas depende del tamaño de éstas, es importante considerar este factor si se pretende medir la efectividad de una tecnología como la estufa Patsari; sobre todo cuando se relaciona la información proporcionada por estos instrumentos con estudios epidemiológicos donde cualquier cambio en la distribución de los tamaños del contaminantes tiene repercusiones directas en la salud.

6.¿Son significativas las concentraciones microambientales y las reducciones de PAH's en función del tipo de estufa utilizada?

La concentración total de PAHs obtenida para usuarias de fogón (2,293 ng/m^3) excede en 3 órdenes de magnitud al promedio publicado por Gustafson et al (2008) donde se analizaron las concentraciones de 27 PAHs en fase gaseosa y asociados a partículas en hogares con y sin estufa de leña en Suecia. Las concentraciones promedio 24-h de algunos hidrocarburos aromáticos policíclicos (PAHs) analizados en este estudio (fluoreno, fenantreno, antraceno, fluoranteno y pireno) fueron 3 veces más altas que los resultados publicados en otros estudios en ambientes urbanos (Ohura et al, 2004).

Se obtuvo una reducción de 66% en la concentración promedio 24-h del total de PAHs en hogares usuarias de Patsari, pero aún así las concentraciones exceden todavía alrededor de 500 veces a las concentraciones publicadas en ambientes urbanos (Gustafson et al, 2008; Ohura et al, 2004) y son similares a las concentraciones reportadas en cerca de 20 estudios ocupacionales (Armstrong et al, 2004). En Suecia como en otros países desarrollados, la incidencia de cáncer pulmonar es mayor en las ciudades que en zonas rurales. La exposición continua a contaminantes carcinogénicos del aire puede ser uno de los factores que influye en esta proporción junto con el consumo de cigarro y otros factores. Los niveles de hidrocarburos aromáticos policíclicos, por las implicaciones en experimentos de toxicología con animales y por los resultados de estudios epidemiológicos, han sido motivo de intensa investigación y monitoreo.

Los promedios encontrados en algunos estudios de contaminación urbana en Suecia se encuentran en un rango de 0.5 a 10 ng/m^3 y por las implicaciones de salud pública que éstos niveles representan, las población se ha propuesto alcanzar un valor promedio diario de 0.1 ng/m^3 de benzo[a]pireno (B[a]P) para el 2020. La realidad rural en México dista mucho de lo que sucede en países desarrollados. Las concentraciones encontradas en este estudio sirven como indicador de la CI por combustión de biomasa, son un llamado de alerta sobre las posibles implicaciones en salud pública y finalmente ponen de manifiesto que usar concentraciones microambientales para estimar exposición puede ser un error con costos irreparables.

La contribución individual a la concentración total de PAHs corresponde con otras publicadas por Bi et al, (2003) y Ohura et al, (2004). Los compuestos que conformaron el 85% del total de PAHs en viviendas usuarias de Patsari fueron fenantreno, fluoreno y naftaleno. El fenantreno fue el compuesto más abundante tanto en la concentración de la cocina como en la estimación de exposición personal. En este proyecto, sólo se evaluaron las concentraciones de los diferentes PAHs en fase gaseosa y dado que los compuestos de mayor peso molecular, menos volátiles, se asocian con partículas de diferentes tamaños y en mayor proporción con las de diámetro más pequeño, es importante profundizar en la caracterización de estos compuestos durante el proceso de combustión doméstica de biomasa.

7.¿Cuál es la relación entre la exposición personal y las concentraciones intramuros de PAHs?

Las reducciones en las concentraciones de exposición personal fueron consistentemente menores que las encontradas en la cocina (66% vs 37%). Este hallazgo coincide con otros estudios (Zuk et al, 2006; Naeher et al, 2001, Brauer et al, 1996).Aunque no se observaron diferencias significativas en las reducción de las concentraciones individuales de PAHs, se obtuvo una reducción del 37% de la concentración total. Para las usuarias de Patsari, las concentraciones de exposición personal del pireno, antraceno, acenafteno y acenaftileno fueron mayores que las concentraciones en la cocina. En los demás compuestos, la exposición personal fue de entre el 70 al 90% de la concentración en la cocina. En las casas con fogón, ninguno de los compuestos presentó concentraciones de exposición personal mayores a las de la cocina y de hecho en 50% de los PAHs (pireno, fluoreno, antraceno, fluoranteno) la exposición personal representó menos del 50% de la concentración de la cocina.

El proceso de combustión es muy complejo y depende de muchos factores. Por eso, no sorprende el hecho de que algunas concentraciones de exposición sean mayores en los hogares usuarios de Patsari comparados con las usuarias de fogón. Las tendencias mostradas en este estudio reflejan claramente que se pueden estar subestimando los beneficios de usar una EE en condiciones de mantenimiento y limpieza apropiadas al usar las concentraciones de la cocina como proxy de los niveles de exposición personal. Recientemente el Global Energy Assessment (2009) publicó que reducciones muy modestas en exposición personal a contaminantes, pueden tener un efecto significativo en la salud de los pobladores. En un estudio con estufas eficientes en Guatemala, se reportó que una reducción del 50% en la exposición personal de las usuarias de fogones abiertos repercutió en un 40% de mejoría en niños con neumonía. El uso de la estufa redujo las medianas de todas las concentraciones de los diferentes PAHs y la mayoría de los picos máximos de concentración

Las concentraciones obtenidas en este trabajo, aún con el uso de la estufa Patsari exceden a aquellas publicadas en estudios no ocupacionales, cuyos resultados están en un rango de 1.09 a 24.7 ng/m^3 (Sisovic et al., 1996; Zmirou et al., 2000) y son similares a los resultados encontrados en estudios ocupacionales de exposición donde las concentraciones van de 1.3 a 397 µg/m^3 (Angerer et al., 1997, Watts et al., 1998, Van Delft et al., 1998, Pyy et al., 1997).

Cuatro compuestos (naftaleno, fenantreno, fluoranteno y antraceno) constituyeron el 85% de la ΣPAH de equivalentes de benzopireno (BaP_{equiv}), lo cual sugiere que, aunque los PAHs de bajo peso molecular no tienen un potencial cancerígeno tan grande como los de mayor peso molecular (asociados a partículas), deben tomarse en cuenta cuando se trata de estudios que evalúen las implicaciones a la salud de una mezcla de compuestos. Debe promoverse la realización de estudios para entender el efecto de cada PAH en el potencial cancerígeno de la mezcla de compuestos. Compuestos como el fluoranteno se han propuesto como indicadores (Böstrom et al., 2002) de contaminación por sus altas concentraciones y su nivel carcinogénico en experimentos con animales de laboratorio. Se ha propuesto un valor de referencia de 2 ng/m3. Comparando los resultados obtenidos en este estudio, es claro que las concentraciones alcanzadas en las viviendas rurales participantes por combustión de leña, sobrepasan en alrededor de 80 veces el valor de referencia en las casas usuarias de fogón y 30 veces las usuarias de Patsari.

CONCLUSIONES

Se pudieron probar las distintas hipótesis planteadas al inicio de esta investigación. En función de los resultados obtenidos se concluye que el uso de la estufa Patsari es una alternativa para mitigar el efecto de la CI.

La concentración inicial en la cocina de $PM_{2.5}$ (1.27 mg/m^3) es 20 veces mayor que el valor estándar de 65 $\mu g/m^3$ establecido por la Norma Oficial Mexicana. Aún cuando la Patsari redujo significativamente las concentraciones, el promedio obtenido (0.35 mg/m^3) es todavía 5 veces más alto que el valor de referencia. Para el CO se obtuvo un promedio de 8.2 ppm para las usuarias de fogón; esta concentración se encuentra en el límite de lo establecido por Norma (8 ppm).

La concentración promedio de exposición personal de $PM_{2.5}$ y CO para usuarias de fogón fueron 0.24 mg/m^3 y 2.7 ppm respectivamente. Para usuarias de Patsari, las concentraciones de $PM_{2.5}$ y CO fueron 0.16 mg/m^3 y 1 ppm respectivamente. Estos valores concuerdan con otros resultados publicados en estudios de CI por combustión de leña. Al igual que con los valores de concentraciones intramuros, estos resultados permanecen fuera de las especificaciones establecidas en la Norma Oficial Mexicana.

Se obtuvo una reducción significativa de en los niveles intramuros de PM y CO (74% y 77%) con la instalación y uso de la estufa eficiente Patsari. Probablemente más importante es si las reducciones encontradas se mantienen consistentemente a lo largo de la distribución de las casas que adoptan la estufa y que los niveles de reducción son mayores cuando se tienen concentraciones iniciales (fogón) muy altas. Igualmente importante es que la reducción de $PM_{2.5}$ al interior de las cocinas fue mayor en las casas que adoptaron la estufa exclusivamente (79%). Se obtuvieron reducciones de 35% y 78% en las concentraciones de exposición personal a PM2.5 y CO respectivamente. Estos resultados son consistentes con otros estudios publicados, donde la reducción en exposición personal es menor comparada con la reducción intramuros (Balakrishna et al., 2002).

Se demostró que las estufas Patsari modifican las propiedades físicas de los contaminantes ya que cambiaron significativamente la distribución de los tamaños de partícula al interior de las viviendas comparada con el uso de fogones. En promedio la Patsari mostró una reducción de 72% en la concentración de $PM_{2.5}$ cuya implicación fue una reducción (de 68% a 48%) en la contribución de masa de las partículas más pequeñas. Este hallazgo puede tener implicaciones en estudios epidemiológicos y de salud porque no se ha tomado en cuenta los cambios en la distribución de los tamaños de partícula y la relación entre concentraciones microambientales y concentraciones de exposición personal.

Con los resultados de las concentraciones de PAHs se demostró que la Patsari modifica la composición y la distribución de los sub-productos de combustión. La distribución de las concentraciones y la contribución de cada PAHs a la masa total y al potencial cancerígeno fueron dependientes del tipo de estufa. Se obtuvo una reducción del 66% en la concentración total de PAHs, sin embargo las concentraciones permanecen 500 veces más altas que aquellas publicadas en estudios urbanos.

Los estudios de monitoreo en contaminación intramuros prometen ser un factor determinante en la certificación del buen o mal funcionamiento de la estufa en campo. Además del beneficio directo de entender las reducciones en las concentraciones de contaminantes intramuros que resultan de la instalación de estufas eficientes, hay otros beneficios potenciales de entender el impacto social, ambiental, de salud y de emisiones de efecto invernadero que este tipo de intervenciones pueden tener.

El éxito de un programa de intervención está determinado por el número de estufas que se usan en óptimas condiciones de funcionamiento y no por la cantidad de estufas instaladas. Desafortunadamente y por las limitaciones del tiempo de monitoreo y los costos asociados, resulta difícil tener una evaluación real de los impactos asociados a la contaminación intramuros.

RECOMENDACIONES

Los estudios de monitoreo en condiciones reales deben considerar el impacto de las EE en relación a la contaminación intramuros y la exposición para los diferentes grupos y patrones de uso de la estufa. Esto por supuesto, implica un esfuerzo logístico por el acceso a las comunidades más remotas y la voluntad de las usuarias a participar en el estudio. Debido a la complejidad del proceso de difusión, implementación y apropiación de EE, el factor "adopción" es motivo de intensa investigación actual. Masera et al (2000) ha sugerido que más que un reemplazo de la tecnología, hay una combinación de usos múltiples de estufas y combustibles en las zonas rurales de nuestro país; aquellos que hacen uso exclusivo de la nueva estufa, los que mantienen el fogón tradicional dentro de la cocina o fuera de ella, aquellos que necesitan un seguimiento minucioso y los que rechazan por completo la nueva estufa. Para estimar la efectividad de un programa de intervención de estufas, es necesario considerar el número de estufas que se adoptan, usan y mantienen más que el número de estufas instaladas.

- Documentar la efectividad de las intervenciones tecnológicas usando como indicador las reducciones de contaminación intramuros y de exposición personal pero con evaluaciones formales en campo ya que, aunque los estudios de laboratorio permiten analizar el máximo beneficio que se puede alcanzar con una tecnología apropiada en óptimas condiciones, la realidad es mucho más compleja e intervienen múltiples factores que condicionan el impacto real.

- Documentar la importancia de la fuente (tipo de leña) en relación con la caracterización de las emisiones por combustión, los niveles de contaminación intramuros y de exposición personal, debido a la heterogeneidad de recursos biomásicos que se utilizan en las localidades rurales de nuestro país.

- Profundizar en el estudio de las propiedades físicas y químicas de los compuestos emitidos por combustión de leña así como posibles impactos en la salud ya que puede haber efectos sinérgicos considerando que la población en riesgo, está expuesta a una combinación múltiple y dinámica de estos compuestos.

- Realizar estudios de salud en mujeres y niños para documentar la relación entre exposición a humo de leña y enfermedades respiratorias agudas y algunos otros efectos adversos; desarrollar equipos adecuados para estudios de monitoreo en campo que puedan proporcionar información veraz sobre los niveles reales de uso de estufas y exposición a contaminantes en diferentes escalas, incluso nacional y finalmente impulsar programas de intervención destinados a mitigar los efectos de quema de biomasa. Estos programas, al menos en materia de estufas, deberían incluir una etapa previa de evaluación del desempeño y funcionamiento, una “certificación” de la tecnología que garantice un funcionamiento adecuado en las condiciones reales de operación.

- Profundizar en los factores que determinan la exposición humana, ¿cuál es la importancia relativa de cada factor a la exposición personal total? Estos factores pueden estar relacionados con la tecnología, características de la vivienda, tamaño, ventilación, factores de comportamiento, etc.

- Impulsar estudios que profundicen en la relación cuantitativa entre exposición intramuros e incidencia de enfermedades.

- Una vez identificados cuáles son los impactos de un programa de intervención, analizar si estos impactos se mantienen a lo largo del tiempo.

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ANEXO 1. THE IMPACT OF IMPROVED WOOD-BURNING STOVES ON FINE PARTICULATE MATTER CONCENTRATIONS IN RURAL MEXICAN HOMES

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The impact of improved wood-burning stoves on fine particulate matter concentrations in rural Mexican homes

MIRIAM ZUK[a], LEONORA ROJAS[a], SALVADOR BLANCO[b], PAULINA SERRANO[c], JEPHTE CRUZ[a], FELIPE ANGELES[b], GUADALUPE TZINTZUN[a], CYNTHIA ARMENDARIZ[d], RUFUS D. EDWARDS[e], MICHAEL JOHNSON[c], HORACIO RIOJAS-RODRIGUEZ[f] AND OMAR MASERA[d]

[a]*General Directorate of Research on Urban, Regional and Global Pollution, National Institute of Ecology/SEMARNAT, Mexico City, Mexico*
[b]*National Center for Environmental Research and Training, National Institute of Ecology/SEMARNAT, Mexico City, Mexico*
[c]*Interdisciplinary Group on Appropriate Rural Technology, Patzcuaro, Mexico*
[d]*Center for Ecosystems Research, National Autonomous University of Mexico, Morelia, Mexico*
[e]*Environmental Health, Science and Policy, University of California at Irvine, USA*
[f]*National Institute of Public Health, Cuernavaca, Mexico*

To evaluate the impact of improved wood burning stoves on indoor air pollution, 53 homes in a rural town in Michoacán, Mexico, were selected from a health intervention study and monitored before and after receiving improved wood-burning stoves. Fine particulate matter — particles with aerodynamic diameter less than 2.5 um ($PM_{2.5}$) — concentrations were measured in the central plaza of the community and in three microenvironments in the home (next to the stove, in the kitchen away from the stove, and outdoor patio). Forty-eight hour mean $PM_{2.5}$ concentrations in homes that burned wood in open fires were 693 $\mu g/m^3$ (95% CI: 246–1338) near the stove, 658 $\mu g/m^3$ (95% CI: 67–1448) in the kitchen away from the stove, and 94 $\mu g/m^3$ (95% CI: 36–236) on the patio. Mean ambient 24-h concentrations in the main plaza of the community were 59 $\mu g/m^3$ (95% CI: 29–92). Paired measurements before and after the installation of the *Patsari* improved wood-burning stove indicate a median 74% reduction in $PM_{2.5}$ concentrations near the stove and 58% reductions in kitchen concentrations, whereas patio and main plaza concentrations remain unaffected. Only 46% of participants reported to use their *Patsari* stoves exclusively during the transition period. Even with the predominant mixed use of the *Patsari* stove with open fires, estimated daily average personal exposures to $PM_{2.5}$ were reduced by 50%.
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Keywords: *indoor air pollution, biomass fuels, improved stoves, developing countries, $PM_{2.5}$.*

Introduction

Evidence from both urban and rural air pollution studies has demonstrated that exposure to particulate matter is associated with increased risk of mortality and morbidity outcomes (Dockery et al., 1993; Bruce et al., 2000; Pope et al., 2002; Dominici et al., 2003). One of the largest sources of exposure to particulate matter in rural environments of the developing world is the burning of biomass for home energy needs, such as heating or cooking. Air pollution levels in homes where biomass is burnt for household energy needs have been found to be up to 50 times greater than the US National Ambient Air Quality Standards (NAAQS) for outdoor 24-h levels set at 65 $\mu g/m^3$ (USEPA, 2002; von Schirnding et al., 2002; Saksena et al., 2003). Exposures to indoor air pollutants originating from the burning of solid fuels depend on a number of factors, including fuel type and quality, housing characteristics, cooking and heating methods, time–activity patterns, and season (Saksena et al., 1992). These factors lead to wide variability of pollution levels between different homes and communities (Saksena et al., 2003). Studies have also found that pollution within the same home can be highly variable between different days of the week (He et al., 2005) and even within the same day (Ezzati et al., 2000a, b) depending on cooking activities.

Exposure to biomass smoke has been associated with increased risk of acute lower respiratory infections in children and chronic obstructive lung disease in adults (Bruce et al., 2000). Also, emerging evidence suggests an association with tuberculosis, adverse pregnancy outcomes, asthma, otitis media, cancer of the upper airways, and cataracts (Bruce et al., 2000; Smith et al., 2004). Smith et al. (2004) found that worldwide 1.6 million deaths and 38.5 million disability adjusted life years are attributed to indoor smoke

1. Address all correspondence to: M. Zuk, General Directorate of Research on urban, Regional, and Global Pollution, National Institute of Ecology/SEMARNAT, Periferico 5000, Colonia Insurgentes Cuicuilco, Mexico City 04530, Mexico.
Tel.: +5255-5424-6460. Fax: +5255 5424 5404.
E-mail: mzuk@alum.mit.edu
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from solid fuels, accounting for 3.5% of the global burden of disease.

Approximately 25% of Mexican homes use wood as their main energy source, either exclusively or in combination with LPG stoves (Díaz and Masera, 2003). These homes are mostly located in rural, indigenous communities. Indoor air pollution studies in several of these communities have encountered elevated levels of particulate matter in the kitchens of homes using biomass fuels (Brauer et al., 1996; Saatkamp et al., 2000; Riojas-Rodriguez et al., 2001). For instance, in the state of Chiapas, 16-h averaged PM_{10} concentrations reached 286 and 589 $\mu g/m^3$ for dry and wet seasons, respectively (Riojas-Rodriguez et al., 2001); in the state of Mexico, 9-h averaged $PM_{2.5}$ concentrations reached 555 $\mu g/m^3$ (Brauer et al., 1996), and in the state of Michoacán, PM_7 concentrations ranged between 655 and 995 $\mu g/m^3$ during the cooking period (Saatkamp et al., 2000).

A number of efforts have been made by Mexican NGOs, government, and academia to address this issue by disseminating improved wood-burning stoves to rural homes with a wide range of outcomes (Masera et al., 2005). Few systematic evaluations have been made on the effectiveness of improved stove programs in reducing indoor air pollution (McCracken and Smith, 1998; Ezzati et al., 2000a; Naeher et al., 2000; Albalak et al., 2001; Bruce et al., 2004). A recent interdisciplinary effort has begun in Mexico to disseminate 1500 improved *Patsari* wood-burning stoves in the state of Michoacán and to comprehensively evaluate their social, health, and environmental impacts (Masera et al., 2005). The air pollution component of this program has included integrated sampling of particulate matter in home and outdoor microenvironments as well as continuous measurements of particulate matter and carbon monoxide both in the home as well as personal sampling (GIRA, 2005). This paper describes the integrated sampling of particulate matter in indoor and outdoor microenvironments using gravimetric methods as well as the estimation of daily average personal exposures to evaluate the air pollution benefits of this improved stove program.

Methods

Study Site and Population

The study took place in the town of Comachuén, an indigenous Purépecha community of approximately 4300 people located in the state of Michoacán in central western Mexico. Over 95% of homes in Comachuén burn wood in open fires for their household energy needs (INEGI 2001), such as cooking meals, preparing tortillas and nixtamal (the corn base for tortillas), and heating water for bathing. The town of Comachuén is located in the Sierra Purépecha, at an altitude of 2600 m above sea level and surrounded by hills. Its geographical location results in frequent thermal inversions in the morning hours, trapping in wood smoke as seen in Figure 1.

Characteristics of Study Homes

Typical homes in Comachuén consist of several separate room structures built around a common patio (Figure 2). Bedroom floors are constructed from concrete (47%), dirt (36%), or wood (14%), and walls are made of either wood (50%) or brick (50%). Kitchens in Comachuén are mostly made with wooden walls (90%) and dirt floors (67%). In over 80% of the homes, the kitchen is separated from the rest of the rooms of the house. Kitchen ventilation is highly variable, depending on the building materials and design of the kitchen. Over 90% of kitchens have space between the wood panels of the walls and between the walls and roof where smoke can escape (Figure 3).

Most homes in Comachuén house several generations of the same family. For instance, one home could house the grandparents, their children and grandchildren. Therefore,

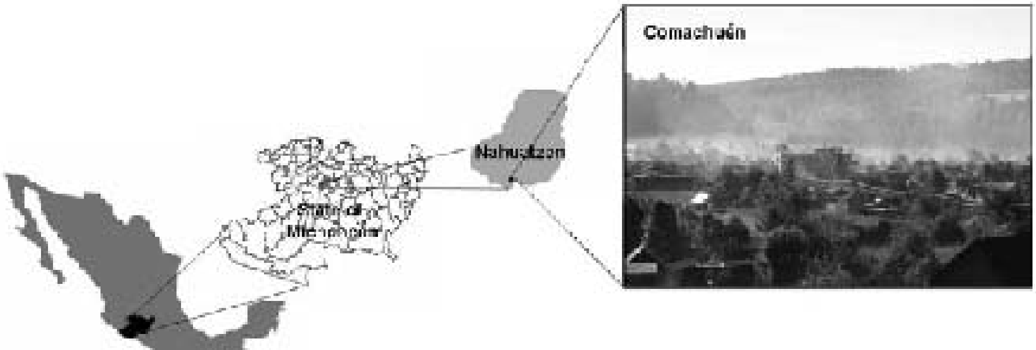

Figure 1. Town of Comachuén in the state of Michoacán.

Figure 2. View from the patio of a typical home of Comachuén.

Figure 3. Kitchen structure with ventilation between the walls and roof.

kitchens and stoves are often shared by several women, and in some occasions, multiple stoves are present in the same kitchen. In some homes, each woman has their own kitchen, leading to multikitchen homes. In Comachuén, nearly 60% of homes have two or more women who participate in cooking activities.

Sampling Plan

From November, 2004 to January, 2005, 53 homes using wood in open fires were visited in the community of Comachuén. Follow-up visits were made from April to May, 2005 in a subset of these homes after the installation of *Patsari* stoves. Both the initial and follow-up visits occurred during the dry season. The initial visits took place during the winter season, with average 24-h temperatures around 12°C (min: 3°C; max: 25°C), whereas the follow-up visits occurred

Figure 4. Open fire on the floor.

during the springtime, with average 24-h temperatures around 17°C (min: 8°C; max: 33°C). Participants were selected from the population of a larger health intervention study of 600 homes, restricted to families with children under 3 years of age and women of child-bearing age, that used wood in open fires for cooking (Figure 4). Additional criteria for inclusion in this study, beyond those used by the health intervention study, were that the kitchens had four walls and a roof. The *Patsari* stoves evaluated in the follow-up visits were donated to study participants (Figure 5).

Before initiating the study, a workshop was held to explain to the community the health impacts of wood smoke, the benefits of the *Patsari* stoves, and the objectives of the study. Field technicians visited the homes of potential participants, explained the objectives of the study, the benefits of the *Patsari* stoves and showed them the sampling equipment that would be placed in their homes. Once a volunteer showed interest in participating in the study, she was read an informed consent form, was asked to sign or mark it, and was left with a copy.

Sampling Methods and Microenvironments

Particulate matter with aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) concentrations were measured over a 48-h period to capture between day variability. Measurements were made in the following three microenvironments: (1) next to the stove (from here on "stove microenvironment"), monitors were placed 1 m horizontally from the stove's

Figure 5. *Patsari* stove.

combustion zone, at least 1.5 m from windows and doors and 1.25 m above the ground; (2) in the kitchen away from the stove ("kitchen microenvironment"), monitors were located on average 1.4 m above the ground and 2.3 m from the stove; and (3) on the patio ("patio microenvironment"), with monitors placed 1.5 m above ground in a central location. The stove measurements were selected to identify the direct impact of open fires and Patsari stoves; the kitchen measurements were aimed to characterize exposures while women were in the kitchen, but away from the stove; and patio measurements intended to determine outdoor concentrations and exposures in an area of the home outside of the kitchen, where a considerable amount of household activity takes place. Additionally, $PM_{2.5}$ concentrations were measured in the central plaza of the community to characterize ambient concentrations.

SKC universal sampling pumps (model 224-PCXR8) were run intermittently (1 min on, 3 min off) at a flow of 4 l/min, with one-stage inertial impactors (SKC Personal Environmental Monitor, model 200) that capture particles on 37 mm Teflon filters (Gelman R2PJ037). Flow rates were measured before and after each sampling period using a calibrated rotameter. Volumes for sampling periods were calculated using the average between the pre-and post-flow rates. Samples in which the post-sampling flow rate or sample time deviated by more than 10% were not used. Filters were pre- and post-conditioned in a controlled environment (22°C ± 3°C and 40% ± 5% RH) and weighted with a microbalance (Cahn model C-35) at the National Center for Environmental Research and Training (CENICA) in Mexico City.

Quality Assurance

Approximately 15% (19 filters) of the total number of samples were collected as field blanks. Procedures for handling blanks were identical to those of exposed filters, only with no air drawn through their surface. Corrections to adjust for filter handling were made by adjusting the mass of sampled filters by the mean mass of the field blanks. Limits of detection (LODs) were estimated as three times the standard deviation of the field blanks divided by the 48-h nominal volume. The average LOD was found to be 2 $\mu g/m^3$. Approximately 10% (12 filters) of samples were duplicates, collocated next to another sampler for quality control. The mean percent difference between collocated samples was 16%.

Questionnaire and Time–Activity Logs

Questionnaires were applied to study participants during the monitoring period by trained field technicians from Mexico City to characterize house characteristics, fuel, and cooking patterns. Participants were asked about their cooking activities during the 2 days of monitoring (e.g. how many meals they cooked and for how many people, cooking duration, time spent near the stove, etc.), and about other potential sources of air pollution such as burning garbage on the patio or smoke entering their home from neighboring homes. In addition, information was obtained on exposure covariates such as fuel type, kitchen location, ventilation, stove location, number of women sharing the kitchen and stoves, *etc*. The follow-up questionnaire was modified to include questions concerning participant's use and maintenance of the *Patsari* stove. The questionnaires were tested in the communities before the study, and were adapted based on observations by field technicians. Time–activity logs were also applied to capture information about all of the participant's activities during the monitoring period, where these activities took place, and for how long. The questionnaires were used to validate time–activity logs in terms of cooking times and locations (where more than one kitchen existed).

Personal Exposure Estimation

To approximate participants' average daily $PM_{2.5}$ exposures during the monitoring period, we calculated time-weighted average concentrations, applying equation (1) (Ozkaynak 1999) to the results obtained from the $PM_{2.5}$ measurements and time-activity logs.

$$\text{Total personal exposure} = \sum_{i=1}^{k} f_i * C_i \qquad (1)$$

where f_i is the fraction of time spent in microenvironment i and C_i is the 48-h $PM_{2.5}$ concentration in that microenvironment. We use this equation, ignoring the temporal variation of concentrations in each microenvironment, owing to the nature of our $PM_{2.5}$ sampling methods. We use stove measurements to characterize exposures during the time spent in the kitchen, because most of the time spent in the kitchen was near the stove and the location of the stove measurements were more standardized than the kitchen measurements. As $PM_{2.5}$ data was not collected in the bedrooms, we assume concentrations in the bedroom and other indoor environments to be the same as the concentrations on the patio. We use patio instead of kitchen concentrations, as the bedrooms and kitchens are separated by the patio in the majority of houses.

Results

Study Population

Of the 53 homes originally in the study, only 39 participants agreed to a follow-up visit and were found to be using their *Patsari* stoves regularly (at least once per day). This may not reflect stove adoption rates *per se* as some women were unavailable for a follow-up visit. Homes were visited 2–3 months after the installation of the *Patsari* stoves.

During the follow-up visit, 92% of homes still had an open fire, either in the kitchen where the *Patsari* stoves were built (42%), on the patio (18%), or in another room or kitchen of the house (32%). Not all of the open fires were necessarily used by the study participant, however, and 44% reported to only use their *Patsari* stoves during the follow-up visit. Approximately half (45%) of the study participants reported to cook with another woman, sharing their open fire or *Patsari* stove.

Microenvironmental Particulate Matter Concentrations

Baseline average concentrations in homes using open fires ranged from 94 $\mu g/m^3$ in the patio microenvironment to 693 $\mu g/m^3$ in the stove microenvironment. Intervention measurements, that is after *Patsari* stoves were installed, showed average levels ranging from 110 to 246 $\mu g/m^3$ in the patio and stove microenvironments, respectively (Table 1). Concentrations are reported at local temperature and pressure.

A clear reduction of $PM_{2.5}$ concentrations is observed in the stove and kitchen microenvironments after the installation of the *Patsari* stoves (Table 1, Figure 6), which were found to be statistically significant (Wilcoxon's test, $P < 0.00001$ for stove measurement and $P < 0.0001$ for kitchen measurement). In contrast, similar levels were found

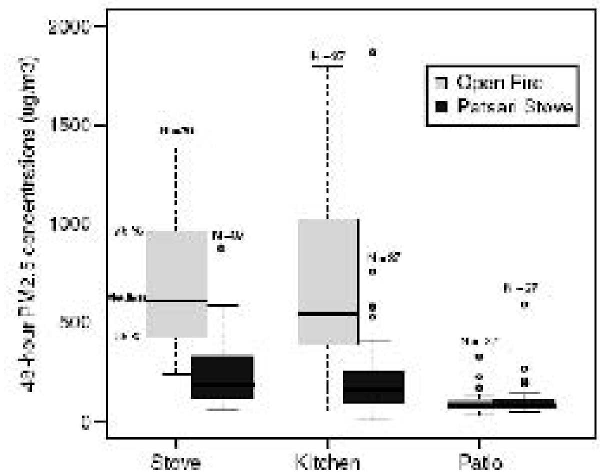

Figure 6. $PM_{2.5}$ concentrations in stove, kitchen, and patio microenvironments.

Table 1. Forty-eight hour $PM_{2.5}$ concentrations in stove, kitchen, patio, and community microenvironments

Microenvironment	N^a	Mean ($\mu g/m^3$)	SD	95% CI ($\mu g/m^3$)	Geometric mean ($\mu g/m^3$)	Median ($\mu g/m^3$)
Open fire microenvironments — baseline						
Stove	36	693	339	246–1338	615	616
Kitchen	37	658	434	67–1448	503	542
Patio	37	94	54	36–236	83	82
Main plaza (24-h)[b]	20	59	18	29–92	60	58
Patsari microenvironments — intervention						
Stove	37	246	175	63–614	197	158
Kitchen	37	233	312	59–664	180	187
Patio	37	110	92	51–295	94	82
Main plaza (48-h)[c]	12	61	8	44–75	60	60

[a] Not all microenvironments were monitored in all the homes during the baseline visits, therefore the sample size for each microenvironment does not equal 53.
[b] Measurements taken on the top of a 1 story building on the main plaza.
[c] Measurements taken on the top of a 2 story building on the main plaza.

in the patio before and after the *Patsari* stoves were installed (Wilcoxon's test, $P \geq 0.53$). Patio concentrations were significantly higher than those observed at the central plaza site (Wilcoxon's signed rank test, $P < 0.000001$). Emissions from the open fire and the *Patsari* stoves developed into homogeneous concentrations in the kitchen, as shown by the fact that levels in the stove and kitchen microenvironments were not significantly different from one another (Wilcoxon's test, baseline open fire $P \geq 0.737$, intervention *Patsari* stove $P \geq 0.516$).

Only paired measurements taken in the same homes before and after the intervention are presented in Table 2, to evaluate the actual reduction of particulate matter from the *Patsari* stove.

Participants' Activity Information
During both the initial and follow-up visits, participants spent on average 19% of the day (4.7h) in the kitchen preparing and eating meals, 14% in the patio (3.3h) washing dishes, sweeping, sewing, and relaxing, 54% in the bedroom (12.9h), sleeping, relaxing, watching TV, and sewing, and 10% outside of the home (2.4h), shopping, washing clothes, collecting water, etc. The rest of the time (3%) was spent in other rooms of the house or neighbor's homes.

Total Personal Exposure Estimates
We combined information on time spent in each microenvironment with their respective concentrations for each participant, to estimate the daily average personal $PM_{2.5}$ exposures of women in Comachuén. Applying equation (1), we found that the daily average personal $PM_{2.5}$ exposure for participants *before* the installation of the *Patsari* stove was 211 μg/m³ ($n = 26$) and *after* the installation of the *Patsari* was 106 μg/m³ ($n = 35$) (Figure 7), signifying an average reduction of 50%, which was found to be significantly different (Wilcoxon's test, $P < 0.000003$).

Each microenvironment contributed differently to participants' daily average exposure to $PM_{2.5}$, with time spent in the kitchen accounting for most of the exposure when using open fires during the baseline measurements. Once the *Patsari* stove was installed and kitchen concentrations decreased, time in the bedroom accounted for a higher fraction of the estimated personal exposure than the kitchen (Table 3).

Mixed vs. Exclusive use of the Patsari Stove
Although participants were encouraged to use their *Patsari* stoves as much as possible, only 17 of them (44%) reported that they exclusively used their *Patsari* stoves during the monitoring period. Sixty two percent of the women who used both the *Patsari* and open fire also shared their stoves with another woman of the house, which is nearly three times higher than those who exclusively used their *Patsari* stoves (Table 4). Although not captured in the questionnaire, the main reason given by participants as to why they continued to use their open fires was the additional time required to cook and heat water with the *Patsari* stove in comparison with the open fire. Furthermore, most participants continued to use the open fire for preparing nixtamal (82%) and heating bathing water (66%).

Although average $PM_{2.5}$ concentrations near the stoves were lower in "exclusive" *Patsari* homes (mean = 205 μg/m³, SD = 126, $n = 16$) in comparison to "mixed" use homes (mean = 279 μg/m³, SD = 210, $n = 20$), these differences were not found to be statistically significant (Mann–Whitney test, $P \geq 0.169$). The median $PM_{2.5}$ reduction for paired measurements found next to the stove in "mixed" use homes was 61%, whereas in "exclusive" *Patsari* homes was 72%.

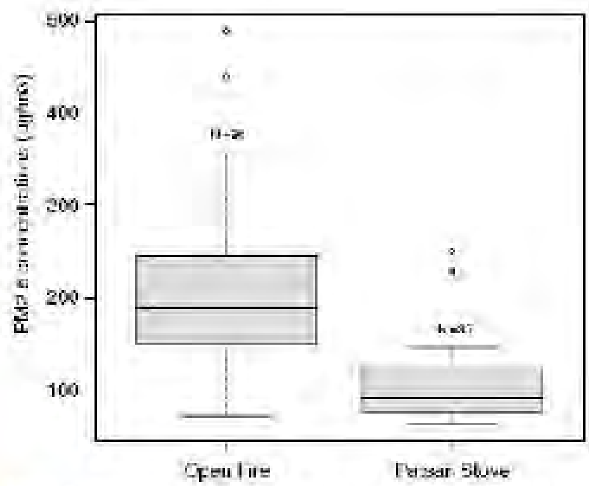

Figure 7. Estimated daily average personal exposures to $PM_{2.5}$ *before* and *after* the stove intervention.

Table 2. Paired differences in $PM_{2.5}$ concentrations for stove, kitchen, and patio microenvironments.

Microenvironment	Median (%)	95% CI	Max (%)	Min (%)	N[a]
% Reduction stove concentrations	−71	−87–5	17	−93	33
% Reduction kitchen concentrations	−58	−90–56	75	−94	34
% Reduction patio concentrations	1	−48–139	229	−60	26

[a] N is not the same as the total number of participants in the intervention visits (39), since not all homes were measured in all three microenvironments for the baseline measurements.

Table 3. Average microenvironmental contributions to estimated total personal exposures.

Microenvironment	Fraction of personal exposures associated with each microenvironment during baseline measurements (±SD)	Fraction of personal exposures associated with each microenvironment during intervention measurements (±SD)
Kitchen	61% (±16%)	35% (±18%)
Patio	7% (±6%)	11% (±8%)
Bedroom	25% (±11%)	47% (±15%)
Other indoor	2% (±4%)	1% (±4%)
Community	5% (±11%)	6% (±6%)

Table 4. Questionnaire results for "exclusive" and "mixed" use of the *Patsari* stove.

	Exclusive *Patsari* use (n=17)	Mixed *Patsari*/open fire use (n=21)
Open fire in the kitchen	35% (six homes)	48% (10 homes)
Open fire elsewhere in the home	47% (eight homes)	57% (12 homes)[a]
Average number of people eating in the house	6 (2–10)	7 (3–15)
Share Patsari stove with another woman of the house	23% (four homes)	62% (13 homes)
Claim that the Patsari is difficult to light	6% (one home)	33% (seven homes)
Use the Patsari to make nixtamal	41% (seven homes)	0%
Use the Patsari to heat bathing water	53% (nine homes)	19% (four homes)

[a]One home had open fires in both the kitchen and patio.

Discussion

We found that kitchen $PM_{2.5}$ levels in homes burning wood in open fires were over 10 times higher than Mexican outdoor 24-h $PM_{2.5}$ standards set at 65 μg/m³ (SSA 2005). Kitchen levels were higher than in other Mexican studies (Brauer et al., 1996; Saatkamp et al., 2000; Riojas-Rodríguez et al., 2001), while falling within the range of comparable studies worldwide (Saksena et al., 2003). The range of concentrations found in the kitchen microenvironment was larger than next to the stove, owing to differences in ventilation and the location of the kitchen microenvironment monitors, which depended on the layout of each kitchen. Ambient outdoor concentrations were elevated in Comachuén as well, exceeding Mexican standards a third of the days monitored.

The installation of the *Patsari* stoves resulted in a median 71% reduction in 48-h $PM_{2.5}$ concentrations near the stove and 58% reduction in the kitchen; however, indoor concentrations remained nearly four times higher than outdoor standards. Several studies that have been conducted in Guatemala to evaluate the impacts of the *plancha* stove on indoor air pollution (Naeher et al., 2000; Albalak et al., 2001; Bruce et al., 2004) found comparable results. These studies, however, were longitudinal in design, and therefore the changes in concentrations found could be influenced by household factors (such as household size, income, design, etc.) and not necessarily to the use of the improved stoves. This study differs in that we tried to reduce the influence of household factors by measuring $PM_{2.5}$ levels before and after the installation of improved stoves in the same homes, although concentration levels could still be affected by differences in activity patterns between the before and after measurements.

No significant impact on patio concentrations was found with the introduction of the *Patsari* stoves, perhaps owing to the influence of neighboring homes and kitchens' emissions coming from the chimney of the *Patsari* stoves or open fires located on the patio. Although much of the reduction in emissions from the *Patsari* stoves occurs because of the improved combustion chambers, a larger study would be needed to determine if the use of chimneys results in increased outdoor air pollution levels. The size and design of this study does not permit us to draw such conclusions, however.

Although the initial visits took place during the winter while the follow-up visits occurred in the spring, both measurement campaigns occurred during the dry season. Average temperatures during the follow-up visits were approximately 5°C higher than during the initial visits; however, ventilation levels in the homes were found to be essentially the same. Participants also reported similar activities in terms of the number of meals they prepared and people eating in their households as well as the amount of time spent outdoors. We assume, therefore, that although the visits occurred during different seasons, this did not have a significant affect on activity patterns or pollution levels.

Estimated daily average personal exposures to $PM_{2.5}$ were 211 μg/m³ with the use of open fires, which is similar to estimates for southern India of 231 μg/m³ (Balakrishnan et al., 2002). The installation of the stoves led to 50% reductions of estimated daily average personal exposures. The majority of exposures to $PM_{2.5}$ originated from time spent in the kitchen during the baseline measurements. Once the *Patsari* stoves were installed, this contribution reduced to less than half of the total exposure, with a concurrent rise in contributions by the other microenvironments. As mentioned previously, temporal variability was not considered, which has been found in other studies to have a significant impact on total personal exposures, with peak emissions episodes contributing to between 31% and 61% of total personal exposures (Ezzati et al., 2000b). The fact that we used 48-h average concentrations may therefore result in underestimates of daily average personal exposures, the contribution of the kitchen microenvironment, and the reductions owing to the improved stoves. Furthermore, while the use of 48-h measurements may smooth over some of the between-day variability, perhaps it does not capture it all, which could lead to greater uncertainty in the results.

We were unable to gather information on bedroom concentrations in this study, as the noise created by the pumps is a significant burden on participants, and therefore we approximated exposures in the bedroom as equivalent to patio levels. As described above, typical home structures (80% of homes) have the kitchen physically separated from the bedrooms, often by a patio. In addition, only four homes reported other sources of pollutants in the bedrooms (such as candles or smoking), leading us to assume that $PM_{2.5}$ levels in the bedroom are most similar to patio levels. During the initial visits, 12-h measurements of $PM_{2.5}$ were taken in the bedrooms of several homes, and average daytime levels of $PM_{2.5}$ were found to be on the order of approximately 150 $\mu g/m^3$ ($n = 28$). Although higher than patio levels, this average only represents daytime levels, and it can be assumed that if taken over the full 48-h period, $PM_{2.5}$ concentrations in the bedroom would be even lower, and thus closer to patio levels than kitchen concentrations. Bedroom concentrations could be either higher or lower than outdoor levels, however, depending on the location and ventilation of the bedrooms and at least seven of the homes had bedrooms attached to the kitchens, which could result in higher bedroom $PM_{2.5}$ levels. Given that over half of participants' time was spent in the bedroom, exposure misclassification could result from applying equation (1) to these situations in rural Mexico, and future measurements in this microenvironment are needed.

Another source of uncertainty in the estimation of personal exposures is the quality of responses obtained from the questionnaires and time–activity logs. Although field technicians were trained in the local community, and came to have a good understanding of the time–activity patterns of the study participants, it was clear that many of the participants did not have a very accurate sense of time. The uncertainty in the time–activity data, therefore, could lead to significant error in the calculations of personal exposures and in determining the contribution of different microenvironments to total personal exposures. Further work is needed to adequately characterize time–activity patterns in rural environments.

Since follow-up visits took place 2–3 months after the installation of the *Patsari* stoves, while some of the participants were still transitioning to the new stove technology, the observed reductions may well change over time. Adaptation to improved *Patsari* stoves can mean a significant behavioral change for many women, as it often includes shifting from cooking on the floor in a kneeling position to the standing position, chopping wood into smaller pieces, longer cooking times, and technology that requires frequent maintenance for adequate performance. The impact of the stoves on indoor air quality may improve with time, as participants use their stoves more, or deteriorate as participants abandon the new technology or fail to provide proper maintenance or use, as has been observed with other stove dissemination efforts (Bruce et al., 2004). It is important, therefore, that longer term impacts of improved stove programs are also evaluated.

Nearly all homes still had open fires during the follow-up visit, used by the study participants or other members of the home. The majority of the participants continued to use their open fires for heating bathing water and preparing nixtamal. Anecdotal evidence from households suggests that pots with bathing water or nixtamal may be heavy to lift up onto the *Patsari* stoves and that heating times for large volumes of liquid may be faster with open fires. Although these activities do not occur on a daily basis, they occur every few days, which has implications for the timing and length of monitoring periods, and epidemiological associations. Stove designs should take these activities into consideration. Furthermore, many homes have multiple families and women cooking in separate or shared stoves and kitchens, which should be taken into consideration for both the stove and study design. Here, we find that women who share their stoves and kitchens are more likely to continue using the open fire in their home, possibly as a result of needing additional cooking space. Another factor that could have had an impact on stove adoption levels is the fact that the stoves in this study were donated to the participants, which could affect participants' attitudes and the value they place on the stoves. Further research should be conducted to determine the implications of the stove donations on its acceptance and use rates.

Even though not all participants in the study made a full transition to their *Patsari* stoves at the time of the follow-up visit, kitchen $PM_{2.5}$ levels in homes that continued to use an open fire were still reduced by over 60%. The difference between stove and kitchen $PM_{2.5}$ levels in "mixed" use homes and "exclusive" *Patsari* homes was not found to be statistically significant; however, this may be related to the sample size or the reliability of questionnaire responses.

This study documents the reductions of indoor air pollution from improved wood-burning stove programs by comparing levels before and after the installation of *Patsari* stoves in rural Mexican homes. We show that the *Patsari* stove can result in large reductions of home $PM_{2.5}$ levels and daily average personal exposures, therefore contributing to cleaner and healthier environments. Both indoor levels and personal exposures are still higher than outdoor air quality standards. Further research is needed on stove use patterns and home energy preferences to determine the sustainability of the environmental benefits of the *Patsari* stoves.

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ANEXO 2. BEYOND FUELWOOD SAVINGS: VALUING THE ECONOMIC BENEFITS OF INTRODUCING IMPROVED BIOMASS COOKSTOVES IN

THE PURÉPECHA REGION OF MEXICO

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Analysis

Beyond fuelwood savings: Valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico

Eduardo García-Frapolli [a,*], Astrid Schilmann [b], Victor M. Berrueta [a,c], Horacio Riojas-Rodríguez [b], Rufus D. Edwards [d], Michael Johnson [d,e], Alejandro Guevara-Sanginés [f], Cynthia Armendariz [a], Omar Masera [a,c]

[a] Centro de Investigaciones en Ecosistemas, UNAM, Mexico
[b] Centro de Investigación en Salud Poblacional, Instituto Nacional de Salud Pública, Mexico
[c] Grupo Interdisciplinario de Tecnología Rural Apropiada, Mexico
[d] Department of Epidemiology, University of California Irvine, United States
[e] Berkeley Air Monitoring Group, United States
[f] Universidad Iberoamericana, Ciudad de México, México

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ABSTRACT

Half of the world population relies on biomass for cooking, with very significant health as well as climate change impacts. Improved cookstoves have been disseminated as an alternative to reduce these impacts. However, few detailed studies about the economic benefits of improved cookstoves (ICS) interventions, including environmental and health co-benefits, exist to date. In this paper we perform a comprehensive economic evaluation of a dissemination program of ICS in rural Mexico. The resulting cost–benefit analysis (CBA) of the Patsari improved cookstove is presented, utilizing estimation of direct costs and benefits, including fuelwood savings, income generation, health impacts, environmental conservation, and reduction in greenhouse gas emissions. The analysis is based on comprehensive data obtained through monitoring studies carried out in the Study Area from 2003 to the present. Results show that Patsari cookstoves represent a viable economic option for improving living conditions of the poorest inhabitants of rural Mexico, with benefit/cost ratios estimated between 11.4:1 and 9:1. The largest contributors to economic benefits stemmed from fuelwood savings and reductions in health impacts, which constituted 53% and 28% of the overall benefit, respectively.

1. Introduction

Global use of biomass for energy provision is common, especially in developing countries, with 2 to 2.4 billion people depending on wood, dung, charcoal and other biomass fuels for cooking (IEA, 2004). This intensive use of biomass is associated with several environmental and health-related problems. The World Health Organization (WHO) estimates wood smoke contributes nearly 3% to the total global burden of disease, resulting in 1.6 million premature deaths each year, including 900 thousand children under five (WHO, 2002). This is similar in magnitude to the burden of disease from malaria and tuberculosis. Millions more suffer every day with difficulty in breathing, stinging eyes, and chronic respiratory disease (WHO, 2006).

Indoor air pollution, inefficient energy practices and unsustainable fuelwood harvesting have been recognized as obstacles to achievement of the Millennium Development Goals (WHO, 2006). Reducing impacts associated with household energy requires changing technology and behaviors in the kitchen, such as the introduction of improved cookstoves (ICS).

ICS dissemination programs were initiated in the 1970s, motivated by a perceived link between deforestation and household energy (Arnold et al., 2003). More recently, the focus has shifted to the health impacts of solid fuel use (Smith et al., 2004; von Schirnding et al., 2001) and these interventions are also valued in terms of the possibility of reducing the emission of greenhouse gases (GHGs, Barnes et al., 1994). As a result, ICS have recaptured the attention of development organizations and donors (WHO, 2006). Because of the large number of people that still cook with biomass, there is growing interest in trading carbon offsets from ICS programs on carbon markets for voluntary reductions, or as part of the Clean Development Mechanism (CDM) of the Kyoto Protocol (Johnson et al., 2009b).

In principle, therefore, ICS can result in reduction of local and global environmental impacts as well as improve the economy and quality of life in local households. Several studies have partially estimated costs and benefits associated with the use of ICS from

* Corresponding author. Centro de Investigaciones en Ecosistemas (CIEco), Universidad Nacional Autónoma de México (UNAM), Antigua Carretera a Pátzcuaro No. 8701 Colonia Ex-Hacienda de San José de la Huerta, 58190, Morelia, Michoacán, Mexico.
E-mail address: frapolli@oikos.unam.mx (E. García-Frapolli).

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socioeconomic, environmental or health perspectives (Jones and Williams, 1998; Gupta and Ravindranath, 1997; Kishore and Ramana, 2002; Mehta and Shahpar, 2004; Kanagawa and Nakata, 2007; Habermehl, 2007, 2008). Critically lacking, however, are in-depth cost–benefit analyses (CBA), based on detailed and consistent field data.

In this paper we perform a comprehensive economic evaluation of a dissemination program of ICS in rural Mexico, in which 80% of the population relies on fuelwood use for primary energy provision (Masera et al., 2005), using detailed data obtained through monitoring studies carried out in the study area from 2003 to the present. The evaluation is done using a CBA that includes both the estimation of direct costs as well as co-benefits in terms of fuelwood savings, income generation, health impacts, environmental conservation at the local level and reduction in greenhouse gas emissions, based on the framework developed by the German Technical Cooperation (GTZ, Habermehl, 1999, 2007).

2. Fuelwood Use and Improved Cookstoves in Mexico

An estimated 27 million people depend on wood for cooking, heating and other domestic tasks in Mexico (Masera et al., 2005), resulting in significant exposure to pollutants in wood smoke. Fuelwood provides approximately 80% of energy used by rural households and 50% of total energy use in rural communities (Díaz, 2000). Most fuelwood is collected or bought from local markets, coming mainly from commercial and non-commercial forest areas, abandoned farming plots under re-growth, and arid regions with shrub cover (Masera et al., 2007).

2.1. The Patsari Cookstove Project

Since 2003, the non-governmental organization (NGO) Interdisciplinary Group of Appropriate Rural Technology (GIRA) and the Ecosystem Research Center of the National Autonomous University of Mexico (UNAM) have disseminated an efficient woodburning cookstove called "Patsari". The Patsari stove is a modified version of the Lorena stove. The Patsari's design includes several improvements including the use of a mould to standardize stove dimensions, custom made parts, and improvements to the combustion chamber and exhaust tunnels to increase efficiency and durability (for a more detailed description of the project see Masera et al., 2007).

Since the project started, over 20,000 Patsaris have been disseminated in different regions of Mexico. 1500 have been disseminated in the Purépecha region (Fig. 1), in which the population is largely rural and indigenous. In this region of Mexico, over 80% of the residences use fuelwood as their primary energy source (Masera et al., 2005), and most fuelwood harvesting comes from forest areas and abandoned farming plots under re-growth, 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. Adoption of Patsari cookstoves results in both higher combustion efficiency and reduced fuelwood consumption during daily cooking activities relative to traditional open fire stoves (Johnson et al., 2008; Berrueta et al., 2008), with significant potential for marketing of carbon savings (Johnson et al., 2009b).

Around 60% of the Patsari cookstoves disseminated in the Purépecha region were to women who purchased the Patsari cookstove. The criteria for disseminating the other 40% was a randomized controlled trial for evaluating health impacts, in which women were chosen because of their reproductive age and had children less than 5 years of age. Within the Patsari project, monitoring and evaluation have had a prominent role. Schematically, in order to have direct feedback from users' groups for stove design, laboratory tests, field trials and pilot tests of prototypes were conducted through participatory techniques. Subsequently, field trials and field monitoring within communities provided direct feedback in a cyclic process to both the stove design and the stove dissemination process through communities (Masera et al., 2007). Several monitoring and evaluation areas (Table 1) were identified to document the major impacts of the Patsari stove and obtain information on the stove innovation–dissemination chain.

3. Methods

The economic analysis undertaken in this study aims at identifying, attaching value and comparing the costs and benefits of improved Patsari cookstove dissemination in the Purépecha region. The analysis

Fig. 1. Map of the Purépecha region in the Mexican state of Michoacan.

Table 1
Data bases and studies generated in the Patsari Project that constitute the basis for the CBA.

Study	Design	Sample groups	Evaluation endpoints
Health impacts (Romieu et al., 2009)	Randomized controlled trial epidemiological study — monthly visits for 20 months to 552 households.	300 control group homes 300 intervention homes with Patsari stoves	Spirometry, blood samples, and health symptoms; Detailed socio-economic characterization of households, including patterns of stove use.
Cookstove performance (Berrueta et al., 2008)	Longitudinal (before and after)	40 households for KPT 4 cookstoves using tortilla making in CCT 4 cookstoves compared for WBT	Fuelwood savings by both exclusive fuelwood and mixed fuelwood and LPG users
Indoor air pollution (Armendariz Arnez et al., 2008; Zuk et al., 2007; Masera et al., 2007)	Longitudinal (before and after)	100 households in two villages	Personal exposures, kitchen and ambient concentrations
Social perception (Troncoso et al., 2007; Velasco, 2008)	Qualitative (focus group plus open interviews) and quantitative (statistical analysis based on a survey).	23 focus groups; 26 interviews with key informants; Interviews to 24 households from 2 villages Survey to 120 households in 6 villages	Attitudes towards improved cookstoves; reasons for adopting or rejecting stoves;
Adoption of cooking technologies (Pine et al., submitted for publication)	Quantitative longitudinal	247 households selected from the 600 households of the health study	Reasons for adopting and using ICS; cookstove intensity of use over time
Measurement of greenhouse gas emissions (GHG) (Johnson et al., 2008; Johnson et al., 2009b)	Cross-sectional	14 laboratory-based water boiling tests (WBTs); 22 field-based WBTs 14 Patsari households and 8 open-fire households during normal daily cooking	Emissions of CO_2, CO, CH_4, black carbon, non-methane hydrocarbons and CO_2e savings from Patsari cookstoves
Fuelwood renewability (Ghilardi et al., 2007; Ghilardi et al., 2009)	Spatial analysis of fuelwood supply and demand (WISDOM Model)	19 municipalities, with 600 villages larger than 100 fuelwood users	Fraction for non-renewable biomass harvesting (fNRB) by village for the Project Area
On-going			
Cookstove monitoring	Permanent cookstove and household monitoring (based on nested design)	500 households with direct cookstove monitoring; 140 households with interviews on stove adoption and use; 90 households with termistors (T-dependent devices) to estimate actual stove daily use; 60 households with seasonal KPT	Cookstove adoption profiles; patterns of use through time; fuelwood savings through time by: types of users (exclusive fuelwood users or mixed fuelwood and LPG; type of village.

Notes: KPT — Kitchen Performance Tests; CCT — Controlled Cooking Tests; WBT — Water Boiling Tests; see Berrueta et al., 2008 for a description of each test.

is consistent with the methodology developed by GTZ (Habermehl, 1999, 2007), which was designed to systematically and comprehensively quantify and value the costs and benefits of an ICS program (Habermehl, 2007). The analysis takes into consideration the costs of construction and dissemination, as well as direct and indirect benefits from the use of Patsari cookstoves compared to the base case in which households cook with traditional three-stone cooking devices. In contrast to many ICS evaluations, where possible this analysis is based on a substantial community based monitoring and evaluation of costs and benefits, therefore most of the metrics used are local.

3.1. Sociodemographic Variables and General Parameters

3.1.1. Adoption Rates

From 2003 to 2008, GIRA disseminated 1672 Patsari cookstoves within the Purépecha region. A quantitative monitoring and evaluation of the project (Pine et al., submitted for publication) estimated that from the total of Patsari cookstoves disseminated, 60%, or 1003 stoves were being used on a sustained long term basis. In general, local households rather than switching to other fuels follow a multiple fuel or fuel stacking strategy (Masera et al., 2000). As a result, from the houses that adopted Patsari cookstoves, 63% are exclusive fuelwood users and 37% combine the use of fuelwood with LPG. Main reasons for multiple fuel use or abandonment relate to the Patsari cookstove not fulfilling some household needs, such as home heating, cooking big amounts of food, heating water for bathing and for cooking nixtamal (Troncoso et al., 2007).

3.1.2. Household Size

Average household size in the Purépecha region is 6.5 persons. To adjust for differential energy needs across household sizes, a "Standard Adult" equivalence factor was used, which relates the fractional energy demand for cooking for a child, a woman or elderly person to that to an adult man of reproductive age. The factors used in terms of sex and ages were: child: 0–14 years, 0.5; female: over 14 years, 0.8; male: 15–59 years, 1.0; and male over 59 years, 0.8 (Guidelines for Woodfuel Surveys, for FAO by Keith Openshaw). The conversion resulted in 4.7 standard adults per home.

3.1.3. Shadow Price for Time Saved

The use of improved cooking devices in rural areas results in time that can be saved either in collecting fuel, cooking or due to a better health. The use of shadow wages in rural areas is controversial. First, because some activities are performed by children or women, which in most cases do not have access to labor markets. Second, because employment opportunities in many rural areas are limited, and those which do exist are usually not available throughout the whole year. Third, because it is debatable whether 1 h saved can be used entirely in other economic activity with the objective of generating income.

With all these in mind, and taking into account that in 2003 29.3% of rural workers had critical employment conditions in Mexico (INEGI, 2006), (those working less than 15 h per week or those working 35 h but making less than one minimum wage), a scenario in which households convert only 25% of their time saved by the Patsari into income generating activities at the prevailing daily income wage was chosen. For activities predominantly undertaken by men, like collecting fuelwood, we used the average daily income in the area (US$15.70) for calculating the shadow price of 1 h of labor (US$2.00, assuming an 8-hour workday). For women we used data from the 2006 Mexican Household Income and Expenditure Survey (INEGI, 2006) to calculate the average daily income of rural women in the study area that are not head of household. In this case, women's average daily income is US$3.30 and the shadow price of 1 h of women's labor is US$ 0.4.

3.2. Variables Determining the Economic Benefits of Cooking with Patsari Improved Cookstoves

The economic benefits of Patsaris were classified in four different groups: (i) fuelwood savings, (ii) job and income generation, (iii) health impacts, and (iv) local and global environmental impacts.

(i) Fuelwood savings

One of the main objectives of an ICS dissemination program is to reduce the demand that households have for fuelwood compared to the traditional devices. These savings impact the household economy in two ways; reducing fuelwood expenses, and reducing time collecting fuelwood. Berrueta et al. (2008) found households exclusively using fuelwood saved an average of 840 kg fuelwood per standard adult per year (67% reduction) after adopting a Patsari, while those using fuelwood and LPG saved an average of 548 kg fuelwood per standard adult per year (65% reduction). Total fuelwood savings for Patsaris in the Purépecha region were estimated at 3448 $t\,year^{-1}$ when fuelwood savings were weighted by the 63% of households that were exclusive fuelwood users and the 37% using fuelwood and LPG (Berrueta et al., 2008).

Local households have different strategies for obtaining their fuelwood. 60% of the households using Patsari cookstoves obtain their fuelwood by collecting it. 20% of households have a mixed strategy in which they collect 70% of their fuelwood and buy the remaining 30% in local markets at an average price of US$0.12 per kg. The last 20% of households buy all their fuelwood in local markets.

Benefits coming from fuelwood savings were valued from the avoided costs due to fuelwood collected and purchased, both valued at the average market price of fuelwood. In order to avoid double counting, the amount of time that individuals saved in fuelwood collection was not included. If households are assumed to save fuelwood at market prices, they do not also benefit in terms of time savings.

(ii) Job and income generation

Evaluation and monitoring studies in the region (Berrueta et al., 2008) found that the average reduction of cooking time per household when using a Patsari cookstove is 1 h per day. On a yearly basis, this means that women can spend 365 h less of their time in the kitchen and can take advantage of this time saved. Of course, there are many debatable issues around this assumption. For instance, it is common that not only one person in the household spends his or her time in the kitchen. In most cases there are other women (daughters, sisters, grandmothers, and so on) or kids and youngsters accompanying or helping in the kitchen. In this analysis only the time saved by the person in charge of cooking was counted irrespective of the number of persons doing household chores in the kitchen. Also, women usually carry out many household activities during the cooking process; therefore the time saved because of using an improved cookstove does not necessarily means that it can be entirely employed in other income generating activities. Half the time was assumed to be exclusively used for cooking and the other half used for other household chores.

With these assumptions, the annual time saved through reduced cooking time in the context of the project amounts to 183,048 h (147 h per cookstove). Then a scenario in which households convert only 25% of their time-savings into income generating activities was used, which gives 45,762 h of effectively saved time (91.25 h per household). In this analysis income or employment-generating effects from the project itself were not considered, such as personnel from GIRA working on the Patsari cookstove dissemination project, the effects in terms of training and qualifications for these groups of persons, or the influence of such effects on the regional economy.

(iii) Health impacts

To understand and quantify the positive health effects of reducing biomass smoke through ICS in rural households, the Patsari project implemented an indoor air pollution survey (Armendariz Arnez et al., 2008; Zuk et al., 2007) and a 668-household health impacts study (Romieu et al., 2009). The health impacts study was a randomized controlled trial in which households from six communities in the Purépecha region were randomized to receive the Patsari stove at the beginning or keep their traditional open fire until the end of the follow-up. 552 households continued participation throughout the study and were followed with monthly visits over 10 months to inquire about respiratory and other symptoms of women and children 5 years old or less. A general purpose questionnaire was administered before the Patsari intervention to obtain information on socio-economic conditions, household characteristics and health-related data.

The benefits due to better health were calculated in accordance to the GTZ methodology. Better health conditions were evaluated based on accidents (burns), as well as acute respiratory disease (measured as the presence of cough) and eye disease (measured as eye discomfort). The reduction in burns attributable to the Patsari intervention was 84%, since reported burn cases in women and children decreased from 49 with the traditional three-stone cooking device to 8 cases when using a Patsari cookstove. The percentage of households with members suffering from acute respiratory disease (measured as cough) was reduced from 74% with the traditional stove to 30% with Patsari adoption. Eye discomfort was reduced from 70% in households using the traditional open fire to 8% when using the Patsari stove. We used GTZ estimates (Habermehl, 2007) for accounting the number of hours lost due to disease (inability to work, visits to health centers, nursing time, among others) when using a traditional open fire stove: 8 h/year due to burns of family members, 80 h/year due to acute respiratory diseases and 16 h/year due to eye-related health problems. Households using the Patsari cookstove saved a total of 40.6 h/year due to better health: 24 h/year from reduced acute respiratory diseases, 9.9 h/year from avoided eye diseases, and 6.7 h/year from the reduction of burn episodes in the kitchen. The total time saved due to better health amounted to 40,722 h, of which only 25% was valued with shadow wages.

The use of Patsari cookstoves has also other positive impacts in terms of avoided costs for health care, both at the household level and at the public health system level. According to data from the public health system (Secretaría de Salud, 2007), the Mexican Government spends US$787 per rural household on health care (amount per capita for the state of Michoacan multiplied by 6 members per household). Some of the questions administered during the epidemiological study inquired about the type of medical attention sought as a result of the reported symptoms by the mother or the child. Almost a third of the medical attention sought was because of respiratory symptoms and diseases, resulting in 31% of expenditures associated with acute respiratory diseases (US$244). When households adopt the improved Patsari stove instead of a traditional cookstove, they reduce the risk of suffering from acute respiratory diseases by 30% and thereby the monetary expenses of these conditions (US$171).

We applied the same percentages to the amount of money spent by rural households on health. According to the data obtained in the epidemiological study, 65% of the households get public medical attention, but the other 35% pays for private medical attention. The yearly amount of money spent by rural households on health is US$437 (amount per capita for the state of Michoacan multiplied by 6 members per household on average), with 31% (US$306) spent on acute respiratory diseases. This amount decreased 30% when households used the improved Patsari stove, which translates to US$131 saved by each household due to the use of improved cookstoves.

(iv) Local and global environmental impacts
The dominant economic value of forest ecosystem goods and services are climate regulation, carbon storage, food production and timber, which can account for approximately 75% of total economic value (Krieger, 2001). In the case of Mexico, Adger et al. (1995) estimated that the total forest area of the country had an economic value of US$4 billion, and that most of those benefits come from functional values of hydrological and carbon cycling.

Recognizing the complexities of valuing a multi-functional ecosystem that has numerous uses by local people and more distant users (Adger et al., 1995), only the benefits of reducing forest impacts coming from unsustainable fuelwood harvesting were assessed in this analysis in terms of costs incurred in afforesting an area of forest whose standing biomass stock is equivalent to the fuelwood savings of the project. For this calculation we took the average biomass density per ha of local forests (223 m^3/ha, on average for degraded forests in the Purépecha Region, Ordóñez et al., 2008), the amount of fuelwood actually harvested (i.e., considering 30% of losses, 156 m^3/ha), and the average wood weight per solid cubic meter (654 kg/m^3). In terms of the Patsari project 3448 ton of fuelwood are saved per year, which translates to saving 38 ha of forest cover. For afforestation costs we included 12 persons/day per ha at US$13.45, 2500 trees/ha at US$0.45 per tree, and US$44.84 of transportation, which accounts for US$1327 per ha of degraded forest in the Purépecha region.

For global environmental impacts we considered the benefits of reducing greenhouse gas emissions. In a comprehensive study that included direct measurement of greenhouse gas (GHG) emissions in the field from both traditional open fires and Patsari cookstoves as well as estimates of non-renewable biomass extraction, Johnson et al. (2009b) estimated that for a sub-sample of 603 households within the project, the average mitigation per Patsari stove was 3.9 tCO_2e/year based on the renewability of fuelwood harvesting for the region, which gives a total of 3912 tCO_2e/year mitigated by the project. The study included measurements of CO_2, CO, CH_4 and total non-methane hydrocarbon emissions. For valuing the economic benefits due to the CO_2e mitigated by Patsari stoves we used an average market price of a ton of avoided CO_2e of US$15.[1]

3.3. Variables Determining the Economic Costs of Cooking with Patsari Improved Cookstoves

For calculating total economic costs of introducing Patsari cookstove in the region we took into account two different sources of costs. First, the individual costs which are associated with the construction of Patsari cookstoves and the annual costs for repairs or spare parts for the stove. Second, the project costs which are the annual expenses made by GIRA for disseminating its Patsari cookstove program. Unfortunately, some costs incurred by the community could not be included such as the cost related to travel time for spare parts or maintenance of the cookstove

(i) Direct costs: construction of Patsari cookstoves
According to GIRA's records, the average costs of constructing a Patsari stove is US$83.30, including materials (sand, bricks, cement, metallic base for the chimney, tubes, *comal*, and so on), which amount to US$53.60, and labor force (technician, bricklayers, and assistants) that add additional US$29.70. Tubes for the chimney and *comals* have to be changed every two years (US$23.67), and the metallic base for the chimney has to be changed every four years (US$10.31).

(ii) Indirect costs: dissemination of Patsari stoves program by GIRA
According to GIRA, indirect costs are related with rising local people's awareness for using improved cookstoves, training local people for cookstoves' construction, follow-up evaluation and monitoring, as well as administrative tasks. GIRA's accounting has divided all these costs per Patsari cookstove built in the area. On a yearly basis, GIRA spends around US $25.30 per cookstove, which is mainly dedicated to the management and monitoring of installed Patsaris.

3.4. Cost–benefit Analysis Method

The CBA was conducted for a period of 7 years and 14 years. This time period was selected since the Patsari cookstove program has been in place for 7 years and, which has been enough time to conduct research on the many aspects needed for developing a comprehensive CBA (see Table 1). Since households that have adopted the improved cookstoves are replacing spare parts after their average life span, we also assume that households using their Patsari stove in the present will remain doing so the following 7 years.

The use of a discount rate in economic valuation has been widely discussed (Krutilla and Fisher, 1985; Markandya and Pearce, 1988; Norgaard and Howarth, 1991; Hanley, 1999), but as Hanley (1999:832) argues, "the social rate of discount for environmental effects may be lower than private rates due to the weight attached by individuals to 'citizenship' motives regarding the environment". Following Sagoff's (1988) arguments, Hanley points out that individuals may have lower time preferences in their roles as citizens as compared to their roles as consumers.

Given these considerations, and the recommended discount rate for stove dissemination programs with highly valued social and environmental aims (Habermehl, 2007), in this assessment we used a simple discount rate of 3%, which is also similar to the discount rate used in health and climate change evaluations (Smith and Haigler, 2008). We explored the effect of varying this rate from 3% to 20% through a sensitivity analysis as have many other studies (De Jong et al., 2000; Habermehl, 2008; Hein and Gatzweiler, 2006).

Table 2
Total economic benefits of Patsari cookstoves.

	Per cookstove US$/year	Per project US$/year
1. Fuelwood savings	400.8	402,030
1.1 Avoided costs due to fuelwood savings	400.8	402,030
2. Job creation and income generation	19.1	19,136
2.1 Benefits from reduced cooking time	19.1	19,136
3. Health impacts	208.6	209,271
3.1 Avoided costs for diseases at household level	131.2	131,611
3.2 Avoided costs for the public health system	73.2	73,398
3.3 Benefit from better health (time saved)	4.2	4261
4. Environmental impacts	103.2	103,508
4.1 Benefit of preservation of forest reserves	44.7	44,833
4.2 Benefit through greenhouse gas reduction	58.5	58,676
5. Total economic benefits	731.7	733,944

[1] The price of carbon at the moment of the data analysis for this paper (September 2009) was approximately US$ 21/tonCO_2 ($15 euros/ton$CO_2e$) according to Point carbon (www.pointcarbon.com). The price actually paid to project sellers varies a lot depending on the project risks and the project sellers bargaining power with brokers. A more complete economic analysis of carbon offset projects need also to account for transaction costs (such as project design, verification, and monitoring) and discount them from the benefits of selling the carbon. Using US$5/tonC as an estimate of the actual benefit to projects, the BC ratio of the project will drop to 10.8 (14 years and 3% discount rate) and 8.6 (7 years and 20% discount rate).

Table 3
Total economic costs from implementing the Patsari Cookstove Project.

		Per cookstove US$	Per project US$
1. Direct costs from Patsari cookstoves construction		83.3	139,308
1.1 Cost of labor	Once	29.7	49,635
1.2 Cost of materials	2 years	53.6	89,673
2. Indirect costs – GIRA's costs from disseminating Patsari cookstoves		25.3	42,275
2.1 Average labor cost	Yearly	4.8	8060
2.2 Average preparation cost	Yearly	1.9	3149
2.3 Average promotion cost	Yearly	1.9	3099
2.4 Average training cost	Yearly	0.9	1575
2.5 Average monitoring cost	Yearly	6.8	11,397
2.6 Average management cost	Yearly	9.0	14,996
3. Total economic costs		108.6	181,583

With all these variables defined, we carried out the CBA by calculating the net present value (NPV) of future cash flow of GIRA's Patsari cookstove dissemination program. NPV represents the sum of all benefits and costs derived from this project during 14 years valuated at the point when the program began in 2003.

$$NPV = \sum B_t - C_t / (1 + i)^t$$

where NPV is the net present value, B_t is the revenue accrued at time t (t = 1,2,3,..., 14 years), C_t is the cost incurred at time t, and i is the discount rate.

4. Results

The gross benefits and costs of the Patsari project are shown in Tables 2 and 3, respectively. We show the results by cookstove and for the whole project. As mentioned in the previous sections, costs are made mainly during the first year of the program, whereas benefits are obtained throughout the time horizon of the analysis. Results of the economic analysis are shown in Fig. 2. Because of the magnitude of the economic benefits of Patsari cookstoves, irrespective of the discount rate and the time horizons chosen, the investment of one dollar in this ICS program has a significant return that varies from US $8.70 to US$11.10.

5. Discussion

The results of our analysis confirm previous economic valuations of ICS projects (Habermehl, 1999; Mutamba and Gwata, 2003; WHO, 2006; Habermehl, 2007; Smith and Haigler, 2008), which have demonstrated that replacement of traditional stoves with ICS can result in significant economic benefits. The economic benefits demonstrated in these analyses were independent of the number of variables and aspects that they have evaluated. Most studies have concentrated on valuing benefits from fuel cost savings. Although this component represents the most extensive benefit in monetary terms in this and previous analyses, household energy interventions have a wider range of benefits. These benefits include reductions in greenhouse gas emissions, increases in productivity because of time saved, reductions in deforestation, improvements in children and women's health as well as reductions in public expenditures within the health sector.

Regardless of the different intervention scenarios, time span, and the discount rates chosen, returns from investing in ICS are substantial in all of these studies. This is clearly illustrated by the Benefit/Cost ratios obtained. While our case study in Mexico showed B/C ratios of between 9 and 11, similar ratios were obtained in a case study in Zimbabwe (13, Mutamba and Gwata, 2003). A case study in Uganda (Habermehl, 2007) showed the highest ratios of all case studies (between 25 and 29), while Malawi (Habermehl, 2008) and China (Smith and Haigler, 2008) showed the smallest ones (between 3 and 6). All these suggest that household energy interventions are a very worthwhile investment, even when choosing high discount rates (i.e., 20%) and short periods of time (i.e., 5 years).

Our study shows that the investment in these kinds of projects seems economically feasible from different stakeholder's perspective, even for the producers, suppliers, promoters or vendors of fuelwood efficient cookstoves. This argument has been supported by other studies (WHO, 2006). From the point of view of ICS' users, our economic analysis reveals benefits in terms of tangible monetary savings for the household economy, as well as time savings valued with shadow wages. For local and federal governments, the investments in household energy interventions would provide preventive instead of palliative measures for improving public health and the environment. Better health status of local populations helps reduce government expenses and subsidies for the health care sector or could be applied for preventive health measures and to combat other diseases. Research has shown that ICS projects can improve health in a very cost-effective way (Hutton et al., 2006), and this kind of intervention compares well with interventions in other major diseases such as malaria, tuberculosis, coronary artery disease and diarrheal disease (Bailis et al., 2009).

Interpretation and comparisons of results, however, need careful consideration, because of the different assumptions and inputs of each CBA. As any other economic valuation method, CBA is highly dependent on data quality and assumptions.

The analysis also shows that Patsari cookstoves result in very significant global benefits, in terms of climate change mitigation. The emissions saved each year per stove (which averaged 3.9 tCO_2e/year) are about twice those of a typical car in Mexico. For a 14-year stove program, a total of ~55,000 tCO_2e would be saved assuming no growth in the number of stoves installed. Using a 10% discount rate, and the project costs outlined above, the cost of mitigating carbon emissions using Patsari cookstoves would amount to $10/$tCO_2e$

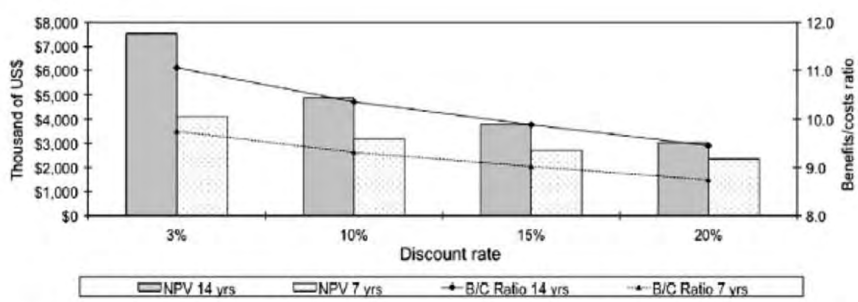

Fig. 2. Net present value (NPV) and benefit/cost ratios results over 7 and 14 years at discount rates of 3, 10, 15 and 20%.

abated and net costs (i.e., including all the benefits) would reach −$104/t$CO_2$e abated. The costs of CO_2e savings from ICS are much lower than the carbon prices for emission permits under a cap and trade system designed to meet Kyoto Protocol reduction targets for Europe and the United States, respectively (US$26–159 and US$53–68 per tCO_2e) and more than 10 times lower than the cost of nuclear energy in England, for example (DTI, 2003). The relatively low CO_2e abatement costs associated with the Patsari are especially pertinent given a recent World Bank study which estimated that the CO_2e mitigation potential for cookstoves in Mexico reaches 19.4 million tCO_2e per year or 222 million tCO_2e by the year 2030. ICS represent 10% of total CO_2e mitigation potential within the country and the largest within the Mexican household energy sector (Johnson et al., 2009a).

ICS also provide tangible local sustainable development benefits, making them a key option for the Clean Development Mechanism. Unfortunately, entry costs of CDM are extremely high for small-scale projects, and the existing approved methodology that is applicable to cookstoves substantially underestimates carbon savings (Johnson et al., 2010). New, simplified and cost-effective methodologies have been proposed (Johnson et al., 2009a) but they have not been adopted yet. As a result, cookstove projects seeking CDM financing will likely be undervalued in terms of their true carbon savings.

Although in a strict sense household cookstoves are a private good, the impacts of households adopting an ICS extend well into the public sphere, because of the direct links between household energy, health, and environmental issues (WHO, 2006). On account of the significant economic benefits, both from a micro and macroeconomic perspective, many developing countries have started a national or large-scale ICS dissemination programs. In the case of Mexico, a national program has already been launched. The Ministry of Development (SEDESOL), the Forestry Commission (CONAFOR) and the National Commission for Indigenous People (CDI), through the Mexican Strategic Program for Climate Change (PECC), aim at disseminating 500,000 ICS for 2012, or 12.5% of total households that use fuelwood for cooking.

With the magnitude of such an enterprise, several aspects learnt from the experience of the Patsari project are worth mentioning. First, it is crucial to understand why a substantial fraction of households do not adopt the technology. According to Troncoso et al. (2007), adoption rates increase for people that had already access to LPG, the user's motivation for testing new technologies, availability of economic resources, and their willingness to participate in new processes. Second, ICS interventions have a poor history of field assessment, even for relatively basic outcomes such as adoption rates or fuel savings. GIRA has done rigorous monitoring because of close relationships with academic institutions and cooperation with government agencies. Under a purely commercial model of cookstove delivery, thorough monitoring would likely be prohibitively expensive, so the development of simplified methodologies and tools are a priority.

Finally, national programs need to have accurate information derived from local and regional monitoring and evaluation of ICS. This is why studies like the ones developed in the context of the Patsari project, including the economic evaluation presented in this paper, can be key inputs for developing a more stringent national policy for disseminating ICS.

While the present study strived to get the most accurate locally-derived data to conduct a CBA, and captures the bulk of the costs and benefits from the Patsari cookstove program, there are several aspects that could be improved in future CBA. An ideal or "best practices" CBA for stove projects should aim at an accurate valuation of all the externalities (co-benefits) and costs associated to the use of improved cookstoves. Four main valuation aspects deserve closer attention: shadow prices for time saved; health impacts; ecosystem services and community-incurred costs. A critical issue in shadow prices is the extent to which local villagers, especially women, have the possibility to translate savings in time into *income generating activities*. Since correctly valuing time is a central aspect of the positive externalities associated with more efficient technologies, we suggest that, rather than relying on standard factors, local data and a detailed analysis are conducted to derive an accurate estimate of shadow prices associated to time savings.

In terms of valuing health impacts, it is logistically unfeasible to perform health studies for the many health impacts associated with smoke form solid fuel use, since each health study would cost millions of dollars and for some endpoints take many years to complete. For this reason literature based assessment of health impacts, combined with locally measured concentrations and exposures to pollutants would be a best practice approach for CBA following the approaches to estimate disability adjusted life years (DALY) used in global burden of disease estimates (Smith and Mehta, 2003). Although the GTZ approach (Habermehl, 2007) for accounting the number of hours lost due to disease was used in the current paper as it allowed for local community based on health symptoms to be included, estimation of DALYs would capture the longer term benefits from avoided disease instead of immediate decreases in health costs. This would more accurately depict the positive externalities of diminishing the negative health impacts associated with the use of open fires.

In relation to forest ecosystem goods and services that are recovered because of reduced fuelwood collection, obtaining the total economic value of forests, including the value of improving soil quality, seems more robust than the use of afforestation costs, although this presents challenges for a multi-functional system that has numerous uses by local people and more distant users. Finally, community costs of ICS dissemination such as additional cost of travel time for getting spare parts for the new stoves would be important to include in a comprehensive CBA of ICS.

6. Conclusions

The present study shows that adequately designed and disseminated improved cookstoves present an economic option for improving health and economic conditions of local people as well as local and global environmental conditions. Benefits from the dissemination of these cookstoves outweigh their costs by 7 fold. While extremely attractive from social, economic and environmental perspectives, many barriers need to be overcome to achieve faster adoption of ICS. These barriers include: 1) insufficient funding for both research and development (many orders of magnitude behind other renewable technologies), including funding for monitoring long-term stove use and adoption patterns; 2) investment (front) costs in ICS are still high for most rural households; 3) benefits from smokeless kitchens are not well understood by local people; and 4) the notion that the success of dissemination programs is measured by the number of stoves installed or sold, instead of by those stoves actually in use is still largely dominant. As a result, monitoring studies and program and user follow up have been a low priority with minimal budgets.

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ANEXO 3. CUESTIONARIO DE CALIDAD DEL AIRE EN INTERIORES Y EXPOSICIÓN

Día (dd/mmm/aa) y clave de revisión ___/_____/___ ______

Día (dd/mmm/aa) y clave de capturista___/_____/___ ______

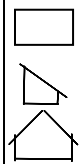
Día (dd/mmm/aa) y clave de recapturista___/_____/___ ______

DATOS GENERALES

IAP_DG **1.-** Localidad		
IAP_DG **3.-** Folio de la vivienda		
IAP_DG **3a**.- Muestreo	Fogón abierto 1	

Notas____
____
____
____
____

COCINA - preguntas para todo el periodo de monitoreo

IAP_C **1**.- Diseño de la cocina	 ……….1 ....……2 ……….3 Otro, especifique______________..........…8	
IAP_C **1a**.- ¿En dónde se construyó la Patsari?	En el mismo cuarto y en el mismo lugar que el fogón anterior...................................0 En el mismo cuarto, pero en diferente lugar que el fogón anterior..........................1 En otro cuarto de la casa ....2 En un cuarto nuevo de la casa ....3 Otro, especifique_________________.......8 No aplica 99	

COCINA cont. - preguntas para todo el periodo de monitoreo

IAP_C **1b**.- ¿En la cocina dónde se encuentra la Patsari hay algún otro fogón? Si si, ¿Dónde está ubicado? ________________	NO..0SI ....1 No aplica o respuesta faltante..................99	
IAP_C **1c**.- ¿Tienen algún otro fogón en la casa ?	NO..0 SI ....1 No contestó ....99 Si la respuesta es NO pasar a la pregunta IAP_C 2.	
IAP_C **1d**.- ¿En dónde se ubica el fogón que está fuera de la cocina principal? Fogon extra A	Patio ....1 Otro cuarto pegado a la casa ....2 Otro cuarto separado de la casa ....3 Otro lugar especifique ______________.....8 No tiene otro fogón 99	

<table>
<tr><td colspan="2">IAP_C 1e.- ¿En dónde se ubica el fogón que está fuera de la cocina principal? Fogon extra B</td><td colspan="3">Patio 1

Otro cuarto pegado a la casa 2

Otro cuarto separado de la casa 3

Otro lugar especifique ______________.....8

No tiene otro fogón ....99</td><td></td></tr>
<tr><td rowspan="7">IAP_C 1f-1k.- ¿Le a hecho modificaciones a su Patsari?</td><td></td><td>NO</td><td>SI</td><td>No Contestó</td><td></td></tr>
<tr><td>IAP_C 1f.- Despegó el comal primario</td><td>0</td><td>1</td><td>99</td><td></td></tr>
<tr><td>IAP_C 1g.- Despegó el comal secunadrio</td><td>0</td><td>1</td><td>99</td><td></td></tr>
<tr><td>IAP_C 1h.- Modificó cámara principal</td><td>0</td><td>1</td><td>99</td><td></td></tr>
<tr><td>IAP_C 1i.- Modificó los túneles</td><td>0</td><td>1</td><td>99</td><td></td></tr>
<tr><td>IAP_C 1j.- Amplio la entrada</td><td>0</td><td>1</td><td>99</td><td></td></tr>
<tr><td>IAP_C 1k.- Otra modificación

Especifique ________________________</td><td>0</td><td>1</td><td>99</td><td></td></tr>
<tr><td rowspan="2">IAP_C 1l-1p .- ¿En los útlimos ocho días ha tenido problemas con la Patsari?</td><td></td><td>NO</td><td>SI</td><td>No Contestó</td><td></td></tr>
<tr><td>IAP_C 1l.- ¿Le cuesta trabajo prender la Patsari?</td><td>0</td><td>1</td><td>99</td><td></td></tr>
</table>

	IAP_C **1m**.- ¿Se le apaga facilmente la Patsari?	0	1	99	
	IAP_C **1n**.- ¿Se le ahoga facilmente?	0	1	99	
	IAP_C **1o**.- ¿Se le regresa el humo?	0	1	99	
	IAP_C **1p**.- ¿No calienta tan rápido como quisiera?	0	1	99	

IAP_C **1q-1s**.- ¿Hace cuántos días...?	IAP_C **1q**.- Limpió la chimenea ....______ IAP_C **1r**.- Sacó las cenizas .... ______ IAP_C **1s**.- Selló los comales .... ______	

COCINA cont. - preguntas para todo el periodo de monitoreo

IAP_C **1t**.- ¿Normalmente usa la Patsari para el Nixtamal?	NO... ... 0 SI.. ... 1 No sabe o no contestó................................ 99	
IAP_C **1u**.- ¿Normalmente usa la Patsari para calentar agua para el baño?	NO... ... 0 SI.. ... 1 No sabe o no contestó................................ 99	

IAP_C **2.-** Nivel de ventilación en las paredes sin contar ventanas. **Criterios:** **Nada-** paredes sin ranuras **Poco-** paredes con algunas ranuras angostas(<1cm) **Regular-** paredes con muchas ranuras angostas(<1cm) o entre 1-3 ranuras de mas de 1 cm **Mucho-** paredes con muchas ranuras de más de 1 cm	Nada ....0 Poca ....1 Regular ....2 Mucha 3	
IAP_C **3**. - Separación techo-pared.	Centímetros 0 0-10 10-20 20-30 >30 **3a**.- Pared 1 ....0 1 2 3 4 **3b**.- Pared 2...........0 1 2 3 4 **3c**.- Pared 3 ....0 1 2 3 4 **3d**.- Pared 4 ....0 1 2 3 4	
IAP_C **4**.- ¿Alguna persona de la familia duerme en la cocina?	NO... ... 0 SI.. ... 1 No sabe o no contestó................................ 99	

IAP_C **5**.- ¿Cuántas personas durmieron en la cocina durante el tiempo de monitoreo? Anotar 99 si no sabe o no contestó	....____	

Preguntas por día

IAP_DIA **1.-** Fecha	Día (dd)____ Mes (mmm) _____ Año (aa)_____	
IAP_DIA **2.-** Descripción del día	Día instalación..1 Día retiro monitores personales ....2 Día retiro 3	
IAP_DIA **3**.- Clave del encuestador	...._________	

Fogón o Patsari

IAP_F **1,3,4,8 a-c-** ¿Qué tipo de combustible usó para cocinar?	Anotar 99 si no contestó la pregunta	a Mañana 0 - NO 1 - SI	b Tarde 0 - NO 1 - SI	c Noche 0 - NO 1 - SI	
	IAP_F **1a, 1b, 1c.-** Leña				
	IAP_F 3a, 3b, 3c.- Olotes				

	IAP_F **4a, 4b, 4c.-** Desperdicios de aserradero				
	IAP_F **8a, 8b, 8c.-** Otro. Especifique: ____________				

IAP_F **9**.- ¿Qué tipo de leña usó?	No usa leña .... 0 Encino…………………….........……… .. 1 Pino……………………………............ 2 Otro……………………………..........….. 8 (Especifique)_______________ Combinación .... 4 No sabe 99	
IAP_F **10**.-¿Usó usted leña que estuviera.....?	Seca.. 1 Humeda... 2 Mojada.. 3 No sabe o no contestó 99	

IAP_F **11**.-¿Usó usted leña verde? Explicar a la Sra diferencia entre verde y mojada.	NO.. 0 SI... 1 No sabe o no contestó............................... 99	
IAP_F **12a-b**.- ¿Para cuanta gente cocinó ? Anotar 99 si no sabe, no recuerda o no contestó	IAP_F **12a**.- Niños .... ____	
	IAP_F **12b**.- Adultos .... ____	
IAP_F **13-** ¿Cuántas mujeres cocinaron en la misma cocina?	0 .... ____ 1 .... ____ 2 .... ____ 3 o más .... ____ No sabe o no contestó 99	

IAP_F **14**.-¿Si tiene estufa de gas, cuántos minutos la usó? Anotar 0 si no tiene y 99 si no recuerda .	....________ min	

Preguntas por día - cont.

IAP_DIA **1.-** Fecha	Día (dd)____ Mes (mmm) ___ Año (aa)____	
IAP_DIA **2.-** Descripción del día	Día instalación..1 Día retiro monitores personales ....2 Día retiro 3	

Humo exterior

IAP_HE **1-** ¿Durante cuántos minutos se quemó basura en el patio? Poner 99 si no sabe o no contestó.	....________min	
IAP_HE **2-** ¿Durante cuántos minutos quemó usted basura? (con ella presente). Si ella la encendió debe ser por lo menos 1 min. Poner 99 si no sabe o no contestó.	....________min	
IAP_HE **3-** ¿Se metió el humo de otro lado a su cocina?	NO... 0 SI.. 1 No sabe o no contestó 99	
IAP_HE **4 -** ¿Se metió el humo de otro lado al cuarto en donde se pusieron los monitores?	NO... 0 SI.. 1 No sabe o no contestó 99	

IAP_HE **5** - ¿Se pasó el humo de la vecina o de la quema de basura al patio en donde se pusieron los monitores?	NO... 0 SI.. 1 No sabe o no contesto 99	

Cigarro

IAP_T **3** - ¿Cuántos cigarros se fumaron en la cocina el día de hoy? Anotar 99 si no sabe o no contestó	....____ _	
IAP_T **4** - ¿Cuántos cigarros se fumaron en el cuarto donde se monitoreó el día de hoy? Anotar 99 si no sabe o no contestó	....__ __	

Otras fuentes

IAP_O **1.-**¿Durante cuánto tiempo utilizó leña u otro combustible para calentar el cuarto que se monitoreó? Anotar 99 si no sabe o no conestó	....______ min	
IAP_O **2-3** - ¿Prendió velas en la cocina? Anotar 99 si no sabe o no contestó	IAP_O **2**.- CUANTAS ....______ IAP_O **3**.- CUANTO TIEMPO ....____ min	

IAP_O **4-5** - ¿Prendió velas en el cuarto que se pusieron los monitores? Anotar 99 si no sabe o no contestó	IAP_O **4**.- CUANTAS ....______ IAP_O **5**.- CUANTO TIEMPO ....____ min	
IAP_O **6**.- ¿Usted cree que el día de hoy cocinó tanto tiempo como cualquier otro día? (¿Fue un día común de cocinado?) **Notas ________________________________**	NO………......................………………... 0 SI……………………….....................….. 1 No sabe o no contestó............................99	

Preguntas por usos de la Patsari o fogón

IAP_DIA **1.-** Fecha	Día (dd)____ Mes (mmm) ___ Año (aa)____			
IAP_DIA **2.-** Descripción del día	Día instalación...1 Día retiro monitores personales ....2 Día retiro 3			
IAP_CA **1a,b**.- Usuaria. Si es otra usaria a la principal contestar sólo las preguntas 1b, 2, 3 y 7	IAP_CA **1a.-** Principal ..1 Otra.........8	IAP_CA **1b** Número de uso del día.. ....____		
IAP_CA **1b.-**. Usó	Patsari...1 Fogón abierto en cocina..2 Fogón abierto en otra cocina ....3 Fogón abierto en patio..4 Fogón abierto en otro lugar, especifique................8			
IAP_CA **2**.- ¿A qué hora prendió la Patsari o el fogón? De entre las 0:00 y las 23:59 horas	....____			
IAP_CA **3**.- ¿Cuánto tiempo estuvo prendido la Patsari o				
IAP_CA **4a-j**.- ¿Qué uso le dió a la Patsarí o al fogón?	USO	NO	SI	No contestó

Describir	IAP_CA **4a**.- Agua para cafe	0	1	99
	IAP_CA **4b1**.- Tortillas	0	1	99
	IAP_CA **4b2**.- Tortillas	0	1	99
	IAP_CA **4c**.- Nixtamal	0	1	99
	IAP_CA **4d**.- Frijoles	0	1	99
	IAP_CA **4e**.- Tamales	0	1	99
	IAP_CA **4f**.- Coser carne,	0	1	99
	IAP_CA **4g**.- Freir	0	1	99
	IAP_CA **4h1**.- Hervir agua para beber	0	1	99
	IAP_CA **4h2**.- Calentar agua	0	1	99
	IAP_CA **4h3**.-¿Preparó comida para vender? Especifique_______	0	1	99
	IAP_CA **4j**.- Otro (alimento, calentarse, secar ropa, licor,etc.) Especifique __________	0	1	99
IAP_CA **5a_b**.- ¿Para cuanta gente cocinó? Si no preparó comida anotar niños 0 y adultos 0 Si no recuerda o no contestó anotar niños 99 y adultos 99	IAP_CA_**5a.-** Niños.................................___ IAP_CA_**5b**.- Adultos.............................___			

<table>
<tr><td>IAP_CA 5.- ¿Cuánto tiempo estuvo cerca de la Patsari o fogón mientras éste estuvo prendido?

Si es en la cocina - estar en la cocina es cerca

Si es en el patio - estar a menos de 3 metros es cerca</td><td colspan="5">...____min

Anotar 99 si no sabe o no contestó</td></tr>
<tr><td>IAP_CA 6.- ¿Cuánto tiempo estuvo el niño menor a 3 años cerca de la Patsari o fogón mientras éste estuvo prendido?

Usar el mismo criterio que la pregunta anterior. Hacer un calculo aproximado con la información que dé la señora.</td><td colspan="5">...____min

Anotar 99 si no sabe o no contestó</td></tr>
<tr><td rowspan="3">IAP_CA 7a,d.- Puertas y ventanas abiertas</td><td></td><td>No hay</td><td>Cerrada</td><td>Abierta</td><td>Medio</td></tr>
<tr><td>IAP_CA 7a.- Puertas</td><td>99</td><td>0</td><td>1</td><td>2</td></tr>
<tr><td>IAP_CA 7d.- Ventanas</td><td>99</td><td>0</td><td>1</td><td>2</td></tr>
</table>

ANEXO 4. CARTA DE CONSENTIMIENTO PARA PARTICIPAR EN EL ESTUDIO

Grupo Interdisciplinario de Tecnología Rural Apropiada (GIRA), Instituto Nacional de Ecología y Universidad de California, Irvine

Calidad del Aire Intramuros, Exposición y Emisiones de Gases de Efecto Invernadero de Estufas de leña Mejoradas en Michoacán, México

Teléfono Pátzcuaro: (434) 342-4467

Dr. Omar Masera Grupo, Interdisciplinario de Tecnología Rural Apropiada

Dr. Rufus Edwards, Departamento de Salud, Ciencia y Política ambiental

Teléfono: 001-(949) 824-4731

NOMBRE DEL PARTICIPANTE:___________________________

Quiénes somos

Somos un grupo de investigación a cargo del Profesor Omar Masera (Grupo Interdisciplinario de Tecnología Rural Apropiada, A.C. y Universidad Nacional Autónoma de México en Morelia) y con la participación del Profesor Rufus Edwards de la Universidad de California, Irving en Estados Unidos y Leonora Rojas Bracho del Instituo Nacional de Ecología. En las mediciones de campo estamos participando: Cynthia Armendáriz, Jephte Cruz Aliphat, Abraham Martínez, Paulina Serrano T., Felipe Angeles y Michael Johnson.

Objetivos del Estudio

Evaluar los niveles de humo o de contaminación generados por las estufas que usan actualmente y que tanto se reduce el nivel del humo en su casa como resultado de la instalación de la estufa mejorada Patsari. El respirar mucho humo se ha relacionado con varias enfermedades como dificultades respiratorias e infecciones.

Nos gustaría invitarla a participar

Aproximadamente 60 familias van a participar en el estudio por un periodo de 5 días en tres ocasiones, una antes de la instalación de la estufa Patsari, otra después de que se familiarize con el uso de la nueva estufa y otra a un año de uso.

Si está de acuerdo en participar, le vamos a pedir que nos conteste unas preguntas al final del muestreo acerca del uso de combustible para la estufa, características de la cocina, prácticas de cocinado y actividades. El cuestionario tardará cerca de 20-30 minutos. Esta información será estrictamente confidencial.

Quisiéramos tener su consentimiento para instalar el equipo que mide contaminantes en su casa. Vamos a poner una caja de plástico, rectangular grande (25 x 35cm) con una serie de monitores (UCB, HOBO, Langan y ciclones) en la cocina, cerca de donde usted cocina. Lo vamos a colocar en alguna repisa, o necesitaremos sujetarlo a la pared. Otro más pequeño lo pondríamos también en la cocina, pero en el área donde comen. Otro en el cuarto que usen con mayor frecuencia y otro en el patio. Vamos a dejar los monitores por dos días, excepto uno pequeño en la cocina que lo dejaremos por una semana. También vamos a poner otro monitor (equivalente al tamaño de una olla de cocina pequeña) por donde se va el humo y en el futuro en la chimenea de gas durante un día. Como no tenemos suficiente equipo en algunas casas instalaremos menos equipo.

También quisiéramos conocer lo que usted está respirando todo el tiempo. Nos gustaría que usara este morral que tiene dos monitores, este redondo que mide partículas y este rectangular que mide un gas tóxico (monóxido de carbono) y lo trajera puesto durante dos días. Cuando se vaya a recostar, se lo quita y lo pone cerca de donde esté usted.

Todo el equipo que se instala es seguro y ha sido utilizado en otros estudios. Si por alguna razón alguien resultara lastimado o su propiedad sufriera algún daño como resultado del estudio, se le dará una compensación y atención médica. También puede manifestar cualquier inconformidad resultado de la colocación de los monitores y nosotros estaremos siempre al pendiente para suspender el procedimiento. Puede abandonar el estudio en el momento que lo desee y no se le hará responsable si llegara a romperse el equipo en su casa.

Su Opción

Antes de que decida participar, los investigadores deben explicarle claramente todo. Deben de usar un lenguaje que usted entienda. Esta forma incluye todos los aspectos de las mediciones. No se le pedirá que haga nada que no esté incluido en este formato y que sea explicado por el investigador.

Toda la información de los cuestionarios será totalmente confidencial. En ningún momento se relacionará su nombre o dirección con los resultados de este estudio. Si tiene alguna pregunta, le invitamos a hacerla en cualquier momento. Si no quiere participar, no hay ningún problema y está en todo su derecho.

Si acepta, estará en libertad de cambiar de opinión en cualquier momento y los investigadores retirarán todos los equipos de medición. Usted no será presionada a hacer nada que no desee.

Que beneficios se obtendrán para sus hijos como sujetos de estudio

El beneficio potencial por participar en este estudio será que va ha ver como se reduce el nivel de humo en su cocina. También nos va a ayudar a darnos una idea de qué tanto se reducen los niveles de humo en casas como la suya por el uso de las estufas Patsari y que puede hacerse para mejorar este diseño. Los resultados de este estudio serán muy útiles en esfuerzos futuros dirigidos a reducir la exposición de la gente para mejorar la salud de los niños de comunidades rurales en México.

Como la compensaremos por su tiempo

Se les va a instalar una estufa Patsari. No habrá ningún costo por su participación en el estudio. No recibirá compensación monetaria por su participación en la investigación.

Preguntas. A quien debe llamar ☎

Si tiene alguna pregunta o queja acerca de las actividades de este estudio, puede contactar a las siguientes personas: Dra. Marta Astier Calderon de Grupo Interdisciplinario de Tecnología Rural Apropiada al teléfono, (01434)34-23-216 o acudir al Centro Comercial El Parián Int. 17, A.P. 152, Pátzcuaro, Michoacán, México, 61609.

También puede contacta a:

El director de la Oficina de Administración de Investigación en la Universidad de California, Irvine, al teléfono, 001-(949) 824-6068, al 001-(949) 824-2125, o a la dirección 300 University Tower, Irvine, CA 92697-7600, EU.

Firma de conformidad

Nombre del participante: ✍_________________________________

Firma o huella digital: ✍_________________________________

Nombre del Investigador: ✍_____________________________

Firma del Investigador: ✍_____________________________

Fecha de hoy: ✍________________________

🗋 Usted se quedará con una copia de respaldo!

ANEXO 5. FORMATOS DE CAMPO PARA MONITOREO DE PM2.5, CO Y PAHs

DATOS GENERALES

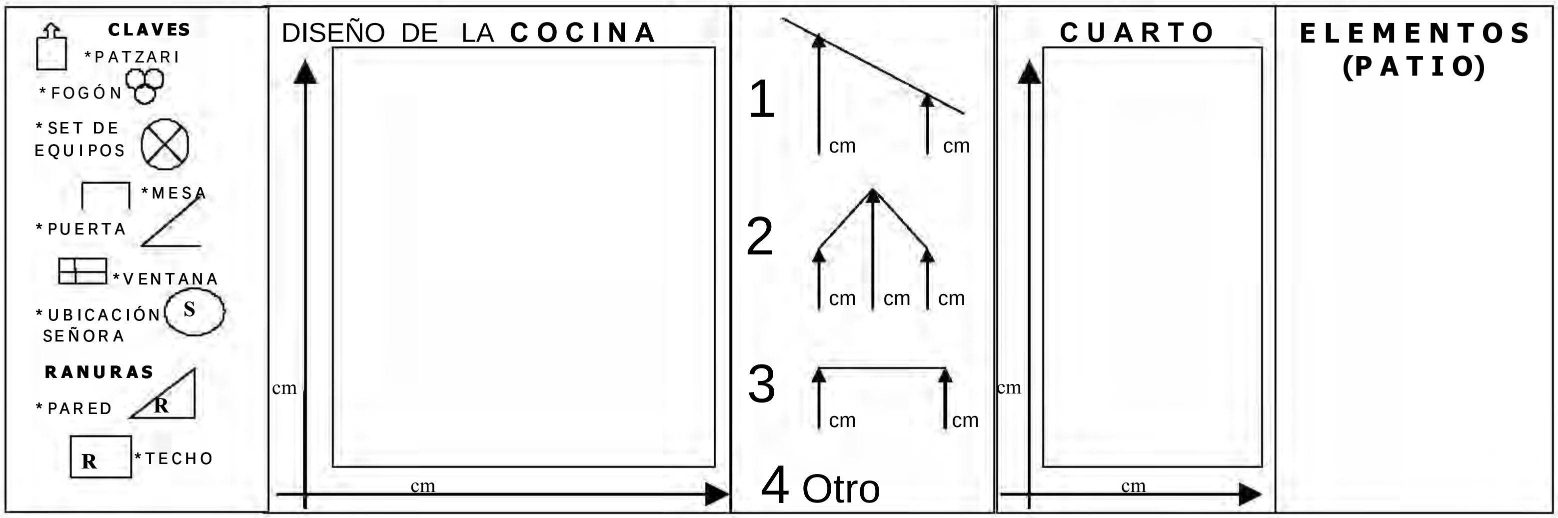
Revisión (fecha y operador) _____/______/_____, ____
Captura (fecha y operador) _____/______/_____, _____
Recaptura (fecha y operador) _____/______/_____, _____

Municipio	Localidad	Domicilio	FOLIO de la vivienda	
	TANACO			

COCINA NUEVA	SI	NO	**Día 1** Instalación	**Día 2** Día siguiente	**Día 3** Desinstalación

GPS		FECHA										
ALTITUD (m)		HORA (de llegada)										
N		TIPO (No.) CASA EN LA SEMANA								Dist. FOGÓN A PATSARI (cm)		
W		1	2	3	4	5	6	7	8			

UBICACIÓN DE LOS MONITORES						
μ-ambiente	ALTURA (cm)	Dist. FOGÓN (cm)	Dist. PATSARI (cm)	Dist. PARED	Dist. PUERTA (cm)	Dist. VENTANA (cm)
EST						
COC						
PAT						
CUA						
COC-2						



PERSONAL DE CAMPO					
A.M.	A.S.	C. A.	J. C.	N.L. / M.J.	Otro

OBSERVACIONES

FOTOS: **EST**		
COC		
PAT		
CUA		
PER		

GUIA
Tiene dos o mas fogones, en donde, si está barriendo o realizando alguna actividad posible fuente de partículas, si es un día ordinario o no, si estuvo cocinando algo especial, si hay fiesta en la casa, si se ve algún otro humo que esté entrando en la casa, tipo de combustible que estén usando al momento de instalar, hirviendo agua, cocinando para los animales, si están usando carbón, dónde se sienta la Sra. a cocinar Si hay algún taller o aserradero al lado de la cocina, si están prendidos tanto el fogón como la patsari.

ESTRUCTURALES
Descripción detallada de las ranuras de la pared, como están distribuidas, si la cocina está en el segundo piso, de qué material es el piso, descripción de las ranuras del techo, si tiene alguna otra ventilación, si la ventana está cerrada o abierta, si hay puerta completa o media, si tiene plásticos en la pared.

MISCELANEA
Si la cocina está llena de gente y algunos otros datos curiosos.

Folio de la vivienda ____________

Revisión (fecha y operador) _____/______/_____, ____

Folio de la vivienda ____________

Captura (fecha y operador) _____/______/_____, _____

Recaptura (fecha y operador) _____/______/_____, _____

	Día 1 (Instalación)	Día 2 (visita)	Día 3 (Desinstalación)
PRESIÓN (mmHg)			
TEMPRERATURA (°c)			

SKC	SKC ID	CICLON / PM ID	FILTRO ID	Monitoreo INICIO			Programado				Monitoreo TERMINO						
				Fecha inicio	Hora inicio	Flujo inicio	Delay time	Sample time	Pump time	Op.	Fecha final	Hora final	Flujo final	Pump time	Sample time	Op.	# de Nota
EST CICLÓN																	
EST IMPACTOR																	
COC																	
PAT																	
BLAN																	
DUP																	

Notas:

____

____

____

Revisión (fecha y operador) _____/______/_____ ___

Folio de la vivienda __________ Captura$_{gral}$ (fecha y operador) ____/____/____ ____ Captura$_{respalco}$ ____/____/___ ____

Recaptura (fecha y operador) _____/______/_____ ____

UCB	UCB ID	Calibración					Monitoreo						# de Nota
		Fecha	Hora inicio	Hora final	Bat cal.	Op.	Fecha inicio	Hora inicio	Op. Inicio	Fecha final	Hora final	Op. final	
EST 5 días													
EST 2 días													
PAT													
CUA													

UCB	UCB ID	Fecha Post cal	Hora post. cal. inicio	Hora post. cal. final	Nombre archivo	C.D. de respaldo	Op. res	Graf ok	Op.	# de Nota
EST 5 días										
EST 2 días										
PAT										
CUA										

Notas:____

____

Revisión (fecha y operador) _____/______/_____ ___

Folio de la vivienda __________ Captura$_{gral}$ (fecha y operador) ____/______/______ ____

Captura$_{respalco}$ (fecha y operador) ____/______/______ ____

Recaptura (fecha y operador) _____/______/_____ ____

HOBO	Equipo #	Bateria inicio	Monitoreo						
			Fecha inicio	Hora inicio	Op. i	Fecha final	Hora final	Op. f	# de Nota
EST									
DUP									

HOBO	Equipo #	Bateria Final	Nombre del archivo	Op. al	C.D. respaldo	Op rep	Graf. Ok.	Op. Graf.	# de Nota
EST									
DUP									

Notas:____

P E R S O N A L

Revisión (fecha y operador) _____/______/_____ ___

Folio de la vivienda ____________ Captura$_{gral}$ (fecha y operador) ____/______/_____ ____

Captura$_{respalco}$(fecha y operador) ____/______/_____ ____

MANDIL: _______ BOLSA: _______ Recaptura (fecha y operador) _____/______/_____ ____

UCB	**UCB ID**	**Calibración**					**Monitoreo**						**# de Nota**
		Fecha	**Hora inicio**	**Hora final**	**Bat cal.**	**Op.**	**Fecha inicio**	**Hora inicio**	**Op. Inicio**	**Fecha final**	**Hora final**	**Op. final**	
PER													

UCB	**UCB ID**	**Fecha Post cal**	**Hora post. cal. inicio**	**Hora post. cal. final**	**Bat. final**	**Nombre archivo**	**C.D. respaldo**	**Op. res**	**Graf ok**	**Op.**	**# de Nota**
PER											

HOBO	**Equipo #**	**Bateria inicio**	**Monitoreo**						**# de Nota**
			Fecha inio	**Hora inicio**	**Op. i**	**Fecha final**	**Hora final**	**Op. f**	
PER									

HOBO	**Equipo #**	**Bateria Final**	**Nombre del archivo**	**Op. F**	**C.D. respaldo**	**Op rep**	**Graf. Ok.**	**Op. Graf.**	**# de Nota**
PER									

Uso del monitor	Todo el tiempo	Regular	Casi no lo uso

Notas:____

Revisión (fecha y operador) _____/______/_____ ___

Captura$_{gral}$ (fecha y operador) ____/______/_____ ____

Captura$_{respalco}$(fecha y operador) ____/______/_____ ____

Recaptura (fecha y operador) _____/______/_____ ____

AMBIENTAL

(Antiguo Centro de Salud)

SKC	SKC ID	CICLON / PM ID	FILTRO ID	Monitoreo			Programado			Op.	Monitoreo			Pump Time final	Op.	# de Nota
				Fecha inicio	Hora inicio	Flujo inicio	Delay time	Sample time	Pump time	In.	Fecha final	Hora final	Flujo final		Fin	
AMB																
DUP																

UCB	UCB ID	Monitoreo						# de Nota	Calibración				
		Fecha inicio	Hora inicio	Op. i.	Fecha final	Hora final	Op. f.		Fecha	Hora inicio	Hora final	Bat cal.	Op.
AMB													

UCB	UCB ID	Fecha Post cal	Hora post. cal. inicio	Hora post. cal. final	Bat. final	Nombre archivo	C.D. respaldo	Op. res	Graf ok	Op.	# de Nota
AMB											

HOBO	Equipo #	Bateria inicio	Monitoreo						
			Fecha inio	Hora inicio	Op. i	Fecha final	Hora final	Op. f	# de Nota
AMB									

HOBO	Equipo #	Bateria Final	Nombre del archivo	Op. al	C.D. respaldo	Op rep	Graf. Ok.	Op. Graf.	# de Nota
AMB									

Notas:____

VOC'S

FECHA	Op. Inicio	Op. Retiro

Universidad de California, Irvine
HOJA DE CAMPO DE VOC´S

1. MUESTREO

BADGE ID	SITE_ ID CASA	FECHA INST. (mm/dd)	HORA DE INST. (hh: mm)	ALTURA (cm)
	EST			

2. COLECCIÓN DE DATOS

BADGE ID	FECHA DE COLECCIÓN (mm/dd)	HORA DE COLECCIÓN (hh:mm)	FECHA DE COLOCACIÓN EN REFRI (mm/dd)	TIEMPO ALMACENADO EN REFRI (hh:mm)

OBSERVACIONES (Incluir INICIALES, FECHA Y HORA): ______________________

____

____

____

____

ANEXO 6. CRITERIOS ESTADÍSTICOS DE SELECCIÓN DE LA MUESTRA

En nuestro estudio trabajaremos con el diseño longitudinal sin grupo de control[1], antes y después de la implementación de la estufa mejorada de leña porque estadísticamente es representativo de acuerdo a la propuesta de Kirk Smith en su manual sobre el uso del equipo USB-PM-1® y USB-HOBOCO-1® para monitoreo de partículas y monóxido de carbono (6), además de algunos factores logísticos y presupuestarios que delimitan las condiciones del estudio.

La contaminación de interiores está relacionada con diferentes factores que hay que considerar al momento de llevar a cabo un estudio de monitoreo:

- Factores relacionados con el combustible: uso exclusivo de leña y uso mixto de leña y gas, tipo, tamaño y cantidad de combustible, humedad, disponibilidad de la fuente y formas de adquisición de la madera.
- Factores de comportamiento: patrones de actividad de uso y frecuencia de cocinado (variaciones entre días de la semana) y habilidad en el encendido de la nueva estufa.
- Factores poblacionales: número de personas para las cuales se cocina (relacionado con el tiempo de cocinado), tipo de comida, tradiciones en la forma de preparar los alimentos y nivel socioeconómico.

---

[1] Básicamente hay tres tipos de estudios que pueden llevarse a cabo para determinar si el uso de estufas mejoradas de leña reduce significativamente los niveles de contaminación de interiores por la combustión (6). Los principales tipos de estudio, así como sus ventajas y desventajas son:

a) Transversal: medir IAP en casas ubicadas en la misma zona geográfica con estufa mejorada y tradicional una vez que la mejorada ha sido implementada. Ventajas: No requiere mucha planeación y se puede llevar a cabo simultáneamente sin tener que considerar un tiempo de seguimiento de las casas. Desventajas: Requiere una muestra muy grande, es difícil reducir los sesgos estadísticos porque las diferencias encontradas en las mediciones de IAP pueden deberse a una serie de factores como volumen de la cocina, tipo de combustible, etc., y no al tipo de estufa.

b) Longitudinal sin grupo control: medir IAP en las mismas casas antes y después de la implementación de estufas mejoradas. Ventajas: Es el diseño que requiere el menor tamaño de muestra, se reduce el sesgo estadístico porque se utilizan las mismas casas para el estudio antes y después. Desventajas: Requiere algunos meses de seguimiento y debe tenerse cuidado con los efectos por las estaciones del año.

c) Longitudinal con grupo control: medir IAP en las mismas casas antes y después de la implementación de las estufas mejoradas pero conservando un grupo control al cual no se le implementa la tecnología alternativa. Ventajas: Es el mejor diseño para mostrar efectos debidos al tipo de estufa porque se puede reducir considerablemente los efectos por las estaciones y el sesgo estadístico por otros factores. Desventajas: Se necesita una muestra muy grande y requiere trabajar en casas a las que nunca se les va a implementar la estufa mejorada por lo que puede haber implicaciones éticas y políticas

- Factores climáticos: temperatura y estacionalidad.
- Factores geográficos: Localización de los grupos de estudio.
- Factores relacionados con la estufa: tiempo de construcción, instrucciones sobre el uso y mantenimiento, tipo, condición y posición en la cocina, niveles de ventilación.
- Factores relacionados con el tipo de construcción de la vivienda: volumen de la cocina, tipos de material usado para las paredes o cercos y tipo de ventilación disponible (cerrada completamente o con aberturas entre los cercos y el techo).

Para el estudio trabajaremos con una confiabilidad del 80%, un error del 5% (valor P = 0.05) y aunque estamos seguros de que el uso de estufas mejoradas no ocasiona incrementos en la concentración de contaminantes al interior de la vivienda, se hará una prueba de dos colas. Esperamos reducciones de 40% mínimo en las concentraciones de partículas y monóxido de carbono según estudios anteriores realizados en Guatemala, en donde, por el uso de la estufa Plancha Mejorada de leña se ve hasta un 85% de disminución en las concentraciones de contaminantes (7).

Para escoger el tamaño de muestra que sea estadísticamente representativa de la población que participa en el programa de implementación de estufas, es necesario considerar algunos parámetros como la reducción de contaminantes esperada por el cambio de tecnología y el coeficiente de variación (COV) que presenten nuestros datos. El COV se define como el grado de dispersión de los datos (desviación estándar, SD) dividido entre la media. Según un estudio realizado en China, el COV promedio que se presenta por el tipo de estufa es 0.9 para estufas tradicionales y 0.7 para estufas mejoradas (6); entonces, adoptando una postura conservadora para nuestro estudio, consideraremos un COV de 0.9. Esta estimación considera 40 casas más un 50% extra (60 casas en total) para asegurar un tamaño de muestra adecuado para los dos monitoreos posteriores (dos y ocho meses de uso de la estufa mejorada) según la sugerencia de Kirk Smith (Fig. 3) (6). Se llevará a cabo un estudio preliminar con 12 casas para corroborar el COV que se propone en este estudio así como para tomar decisiones sobre la forma de estratificar la población para incluir casas que usan exclusivamente leña y casas de uso mixto.

D.E.M. \ COV	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
0.1	8	31	71	126	196	283	385	502	636	785	950	1130	1326
0.2	2	8	18	31	49	71	96	126	159	196	237	283	332
0.3	1	3	8	14	22	31	43	56	71	87	106	126	147
0.4	0	2	4	8	12	18	24	31	40	**49**	59	71	83
0.5	0	1	3	5	8	11	15	20	25	31	38	45	53
0.6	0	1	2	3	5	8	11	14	18	22	26	31	37
0.7	0	1	1	3	4	6	8	10	13	16	19	23	27
0.8	0	0	1	2	3	4	6	8	10	12	15	18	21
0.9	0	0	1	2	2	3	5	6	8	10	12	14	16
1.0	0	0	1	1	2	3	4	5	6	8	9	11	13

D.E.M. diferencias entre medias

Fig. X. Sugerencia estadística del tamaño de muestra para el estudio longitudinal antes y después sin grupo de control, Kirk Smith, 2003 (6).

ANEXO 7. SCRIPT EN R DEL ANÁLISIS MULTIVARIADO NO PARAMÉTRICO

```
o<-read.table("MANOVAr8C.txt",header=F)

datos<-data.frame(o)

x<-datos$V1

resp<-datos[,-1]

set.seed(0)

B <- 5000


#Paso 1: Compute the Th’s statistics on observed and permuted data

ptest2s<- function(Y,x,B,statistic)

{

source("studT")

# tambien se puede correr usando source("http://www.gest.unipd.it/~salmaso/web/studt.r")

#INPUT:

#Y: a data frame or matrix, with n rows corresponing to observations and k columns to variables (hypotheses)

#x: a vector of integers corresponding to observations (rows) class labels. The labels must be 1 (control) and 2 (treatment)

#B: the number of permutations
```

```
#statistic: Student's t statistic (default) or "Tmax" statistic (with ordered categorical data) comparing the treatment with the control

#OUTPUT

#T: Bxk matrix of test statistics (1st row = obs)

#P: Bxk matrix of raw p-values (1st row = obs)


n1<-sum(x==1)

n2<-sum(x==2)

n<-n1+n2

Y<-as.matrix(resp)

k<-dim(Y)[2]


mB<-apply(matrix(1:n,n,B),2,sample)

mB[,1]<-1:n


Z<-as.matrix(Y)

Z.star<-Z

T<-matrix(NA,B,k)


if (statistic=="Tmax"){

for (b in 1:B){
```

```
Z.star<-as.matrix(Z[mB[,b],])

T[b,]<-apply(Z.star,2,function(col)

{round(Tmax(col[x==1],col[x==2]),7)})}

}


else

{

for (b in 1:B)

{Z.star<-as.matrix(Z[mB[,b],])

T[b,]<-apply(Z.star,2,function(col)

{round(studT(col[x==1],col[x==2]),7)})}

}

return(T=T)


}


T <- ptest2s(Y,x,B,"Student")


#Paso 2: Perform the combined tests Tmax, Tsum, and TssT2 by


maxT <- apply(T,1,max)
```

```
sum(maxT[-1]>=maxT[1])/(B-1)

sumT <- apply(T,1,sum)

sum(sumT[-1]>=sumT[1])/(B-1)

ssT2 <- apply(T,1,function(row){sum(sign(row)*(row^2))})

sum(ssT2[-1]>= ssT2[1])/(B-1)


#Paso 3: Check if at least one Th is greater than c——————————————h(1 - )


#alpha <- 0.05

#c1 <- sort(T[-1,1])[B*(1-alpha)]

#c2 <- sort(T[-1,2])[B*(1-alpha)]

#c3 <- sort(T[-1,3])[B*(1-alpha)]

# Se deben de incluir tantos c`s como variables respuesta haya en la matriz

#T[1,] > c(c1,c2,c3)


alpha <- 0.05

c1 <- sort(T[-1,1])[B*(1-alpha)]

c2 <- sort(T[-1,2])[B*(1-alpha)]

c3 <- sort(T[-1,3])[B*(1-alpha)]


c4 <- sort(T[-1,4])[B*(1-alpha)]
```

```
c5 <- sort(T[-1,5])[B*(1-alpha)]

c6 <- sort(T[-1,6])[B*(1-alpha)]


c7 <- sort(T[-1,7])[B*(1-alpha)]

c8 <- sort(T[-1,8])[B*(1-alpha)]

c9 <- sort(T[-1,9])[B*(1-alpha)]


#c10 <- sort(T[-1,10])[B*(1-alpha)]

#c11 <- sort(T[-1,11])[B*(1-alpha)]

#c12 <- sort(T[-1,12])[B*(1-alpha)]


#c13 <- sort(T[-1,13])[B*(1-alpha)]


# Se deben de incluir tantos c`s como variables respuesta haya en la matriz

#T[1,] > c(c1,c2,c3,c4,c5,c6,c7,c8,c9,c10,c11,c12,c13)

T[1,] > c(c1,c2,c3,c4,c5,c6,c7,c8)


#Paso 4: compute the p-values of the consonant Tcsum and TcssT2 tests

#ind <- (T[,1]>c1|T[,2]>c2|T[,3]>c3|T[,4]>c4|T[,5]>c5|T[,6]>c6|T[,7]>c7|T[,8]>c8|T[,9]>c9|T[,10]>c10|T[,11]>c11|T[,12]>c12|T[,13]>c13)

ind <- (T[,1]>c1|T[,2]>c2|T[,3]>c3|T[,4]>c4|T[,5]>c5|T[,6]>c6|T[,7]>c7|T[,8]>c8)
```

```
sum(sumT[ind]>=sumT[1])/(B-1)

sum(ssT2[ind]>=ssT2[1])/(B-1)


#Paso 5: Check noninferiority with = 1/2

eps <- 0.5

Y<-as.matrix(resp)

ct <- qt(1-alpha,length(Y)-2)

delta <- eps/(mean(apply(Y,2,sd)))

T[1,] + delta > c(ct,ct,ct)


#Paso 6: simultaneously test noninferiority and superiority by

ind2 <- (T[,1]+delta>ct & T[,2]+delta>ct & T[,3]+delta>ct)

sum(maxT[ind2]>=maxT[1])/(B-1)
```

ANEXO 8. METODOLOGÍA PARA EL USO DEL EQUIPO HOBO

Equipo:

Monitor HOBO-CO

Cable serial PC-3.5 Logger a puerto PC COM

Discos CD-ROM

Escritorio:

El fabricante del Programa Boxcar Pro sugiere el uso de Pentium 4 o posteriores con 24 MB en RAM, Windows 95/98/NT4 o posterior (procesador mínimo de 486/66Mhz con al menos 16 MB en RAM).

Puerto COM libre con conector 9-pin para comunicación serial (o adaptador para 25 pin) y manejador de CD. Instalar todo el software en el escritorio.

Preparación del monitor HOBO-CO anterior a la instalación en campo:

El intervalo y las condiciones de muestreo deben ser programados antes del traslado a campo.

1. Conectar cable serial a puerto COM
2. Abrir el programa boxcar en la computadora
3. Conectar cable serial al monitor HOBO-CO
4. Seleccionar “launch” del menú
5. Verificar estatus de la batería
6. Seleccionar “enable/disable chanels”. Seleccionar los canales 1 (0-125 ppm) y 2. Aplicar
7. Seleccionar 10 segundos en “interval duration”
8. Etiquetar el equipo con la clave diseñada para identificar la casa
9. Seleccionar “delayed start”. En las cajas de la derecha, insertar fecha y hora deseada para el comienzo del funcionamiento del equipo
10. Asegurar que no esté seleccionada la caja “wrap” de los datos
11. Seleccionar “Start”
12. Seleccionar “continue” de la pantalla con recordatorio de “enable chanel”
13. Haga clic en “OK” para borrar los datos viejos del monitor
14. Desconecte el cable del monitor y presione “OK”…, observe que el monitor comience a medir los niveles de CO en el tiempo programado

15. Verifique que el monitor esté prendido observando una luz centelleante cada dos segundos. Cuando está apagado, la luz no debe parpadear.

Instalación del monitor en campo

1. Aproximadamente 100 cm. Del perímetro externo de la estufa
2. Altura aproximada de 125 cm. del suelo al equipo
3. Como mínimo, 150 cm. de puertas y ventanas

Vaciado de datos

1. Conecte el cable serial a puerto COM
2. Abrir el programa boxear
3. Conecte el cable al monitor
4. Seleccionar "logger" del menú de cabecera. Cuando aparezca las opciones, seleccionar "readout"
5. Deberá aparecer una ventana con las palabras "connecting" y "HOBO found". Otra ventana aparecerá diciendo "offload". Espere a que se vacíen los datos en el escritorio
6. Desconecte el cable y seleccione "OK"
7. Aparecerá una ventana con el letrero "save as". Seleccione el directorio y la carpeta así como el nombre del archivo en el que guardará su información. Marque "Save". El programa desplegará una gráfica de los datos obtenidos. Verifique: a) El periodo de monitoreo, b) que los datos no fluctúen a lo largo de la gráfica y c) que los datos no aparezcan anormalmente de cualquier otra manera
8. Verifique la caja en la hoja de muestra etiquetada "time series plot check"

Respaldo de Archivo de datos

1. Al final de cada semana los periodos de medición de nuevos datos deben salvarse en CD, claramente identificados
2. Una vez respaldados, los archivos deberán moverse al directorio de respaldo de datos.

ANEXO 9. METODOLOGÍA PARA EL USO DEL EQUIPO UCB

Equipo:Monitor de partículas UCB con la versión 4.7 o posterior

Cable DB9 con conexión a puerto COM

Software para monitor de partículas UCB instalado en computadora, versión 1.3.1 o posterior

CD's para respaldo de datos

Escritorio: Pentium 4 o posterior con 24MB en RAM y Windows 2000 o versiones actualizadas (mínimo procesador 486/66Mhz con 16MB en RAM). El sistema requiere por lo menos un puerto COM libre usando un conector 9 pin para comunicación serial (o adaptador para 25 pin) y lector de CD con acceso a escritura. El software para el monitor de partículas UCB requiere el programa ejecutable DOTNET.FX de Microsoft para funcionar.

Es importante tener en cuenta que el reloj del monitor UCB se sincroniza con el de la computadora. Si se usan tiempos de dos computadoras diferentes, los resultados no serán comparables. En cada programación del equipo se debe sincronizar la hora.

Programación del monitor UCB

Los intervalos y las condiciones de muestreo deben programarse con anterioridad al trabajo de campo. Cierre otras aplicaciones requieran el puerto COM.

1. Conecte el cable serial al puerta COM
2. Abra el programa administrador del monitor UCB. Deberá aparecer una pantalla inicial
3. Conecte el cable serial al monitor
4. Asegúrese que el monitor tenga pila
5. Seleccione "next"
6. verifique el estatus de la batería. Para periodos de 48h de monitoreo, es necesario que la batería tenga al menos 7.5 V
7. Confirme que la versión del programa sea 4.7 o posterior en la parte inferior izquierda de la pantalla
8. Verifique que aparezca el número de identificación del UCB en la parte inferior izquierda

9. Confirme que los valores de humedad y temperatura sean razonables (que no sean por debajo de 100). También observe que los sensores estén funcionando (deberán variar ligeramente hasta estabilizarse)
10. Seleccione "configure this device"
11. Seleccione "next"
12. Deberá abrirse una pantalla de configuración
13. Sincronice el reloj del monitor con el de la computadora marcando la palabra "synchronize" y finalmente "OK"
14. Seleccione la fecha y hora en la que el equipo deberá funcionar. Marque una hora próxima en un intervalo adecuado con 00 segundos. Escoja el número de horas que desee que el monitor grabe en la siguiente ventana. Para un monitoreo de 48 h seleccione 60 h para dar margen a los tiempos de calibración, traslado al campo y reposo.
15. Seleccione intervalo de muestreo 1 (un valor será registrado cada minuto)
16. Seleccione muestras por intervalo 60 (los últimos 60 segundos del minuto serán usados como referencia para calcular el valor que será registrado cada minuto)
17. Seleccionar la profundidad del filtro 2 (filtro exponencial 0= no filtro, máximo = 4)
18. Seleccione "launch program". Confirme que los datos son correctos en la caja de diálogo
19. Anote la información en el formato de campo para monitor UCB

Calibración en bolsa Ziploc

1. Después de que el monitor UCB ha empezado a registrar valores, colóquelo en una bolsa de plástico Ziploc. Cierre la bolsa herméticamente asegurando que quede un remanente de aire dentro.
2. Anote el tiempo de calibración en el formato de campo
3. Después de 40 min, saque el monitor y anote la hora en el formato de campo
4. Repita el procedimiento al terminar el periodo de monitoreo en campo
5. Es importante registrar las horas ya que esta información será usada en el análisis de los datos

Instalación del monitor UCB en campo

1. Aproximadamente a 100 cm del perímetro exterior de la estufa
2. A una altura de 125 cm del piso
3. Mínimo a 150 cm de puertas y ventanas de ser posible
4. Si se usa el platillo de soporte sobre la pared, coloque el equipo en él

Vaciado de los datos

1. Conecte el cable serial a la computadora
2. Cierre otras aplicaciones que requieran el puerto COM
3. Abra el programa administrador del monitor de partículas UCB. Deberá aparecer una pantalla inicial
4. Conecte el cable serial al equipo UCB
5. Seleccione "next"

6. Seleccione “Offload data from this device”
7. Aparecerá una ventana que muestra el vaciado gradual de los datos
8. Se mostrará una gráfica de resultados. Asegúrese de que la caja para dejar los datos en el dispositivo esté seleccionada. Marque el botón de “save as”. Seleccione el directorio, carpeta y archivo en el que guardará los datos y haga clic en “save”
9. Seleccione “next”. Aparecerá una ventana confirmando que los datos han sido guardados, bajo que nombre, y las condiciones para el periodo de medición. Los datos podrán verse en el programa “data browser”. Si esta pantalla no aparece, repita el procedimiento de vaciado
10. Verifique: a) El periodo de monitoreo, por ejemplo, que no se haya parado antes de lo programado, b) que los datos no fluctúen a lo largo de la gráfica, c) los sensores no deben reportar valores muy altos o muy bajos y d) que los datos no sean anormales en algún sentido

Procesamiento de los datos

1. Abra el archivo .ucbpm (UCB particle monitor data file) en el programa “UCB data browser”
2. El administrador del dispositivo UCB, deberá desplegar una gráfica de los datos vaciados
3. Alimente la hora para la calibración anterior al muestreo en la caja superior. Este dato se obtiene del formato de campo
4. Meta el periodo de tiempo para el muestreo (observe que este no incluye el transporte o calibración). Estos datos también se obtienen del formato de campo llenado previamente
5. Meta los parámetros para las constantes de cámara y regresión. Los valores definidos para la constante de regresión, son aquellos calculados para cada dispositivo específico en Berkeley
6. Seleccione el botón “calculate mass”

Para exportar los datos:

1. Seleccione “file” y “export to CSV”. Esto salvará el archivo de datos como un archivo de lectura en otros programas estadísticos (CSV= comma separated variables)

Para salvar estadísticas como archivo de texto

2. El programa “UCB data browser” desplegará las estadísticas para el periodo de muestreo del lado derecho de la pantalla. Seleccione “save stats” para salvar estos datos en un archivo de texto

Respaldo de la información

3. Cada semana, deberá salvar los archivos en CD, con número de identificación adecuado para cada dispositivo

4. Una vez respaldados, los archivos de datos de la computadora deberán moverse al directorio de respaldo.