LETTER

Promoting LPG, clean woodburning cookstoves or both? Climate change mitigation implications of integrated household energy transition scenarios in rural Mexico

M Serrano-Medrano1,4,6, C García-Bustamante2, V M Berrueta3, R Martínez-Bravo4, V M Ruiz-García4,5, A Ghilardi1 and O Masera4

1 Centro de Investigaciones en Geografía Ambiental (CIGA), Universidad Nacional Autónoma de México (UNAM), Antigua Carretera a Pátzcuaro 8701, Morelia CP 58190, Michoacán, Mexico
2 Escuela Nacional de Estudios Superiores Unidad Morelia, Universidad Nacional Autonoma de Mexico (UNAM), Michoacán, Mexico
3 Grupo Interdisciplinario de Tecnología Rural Aplicada (GIRA), Pátzcuaro, Michoacán, Mexico
4 Laboratorio de Bioenergía y Laboratorio de Innovación y Evaluación de Estufas de Biomasa (LINEB) Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México (UNAM), Antigua Carretera a Pátzcuaro 8701, Colonia Ex-Hacienda de San José de la Huerta, 58190 Morelia, Michoacán, Mexico
5 Facultad de Ingeniería, Universidad Nacional Autonoma de Mexico (UNAM), Avenida Universidad 3000, Ciudad Universitaria. CP 04510, CDMX, Mexico
6 Author to whom any correspondence should be addressed.

E-mail: mttserrano@gmail.com, aghilardi@ciga.unam.mx, cgarcia@enesmorelia.unam.mx, vberrueta@gira.org.mx, victor_ruizgarcia@yahoo.com and omasera@gmail.com

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Abstract

This study examines the expected mitigation of greenhouse gases (GHG) and black carbon emissions associated with the transition from traditional biomass to clean fuels and clean woodburning cookstoves (CCS) in the Mexican residential sector for the period 2014–2030. We developed a spatial-explicit model at a county level to understand the GHG trade-offs associated with different spatial-temporal CCS and clean fuels dissemination strategies. A business as usual (BAU) and three alternative scenarios with different targets for CCS and LPG dissemination were constructed. Results show that a scenario focusing exclusively on a fast LPG-penetration does not deliver the largest GHG benefits, as there is substantial stacking with traditional open fires. On the contrary, the combination of CCS plancha-type stoves disseminated in regions with high non-renewable fuelwood harvesting (fNRB) together with LPG, allows minimizing of stacking with traditional fires and provide the largest benefits. Also, different scenarios result in contrasting spatial distribution of target counties and mitigation benefits, and therefore have important public policy implications. Cumulative mitigation ranged from 50 MtCO2e to 126.3 MtCO2e depending on the scenario, representing from 14% to 35% of BAU emissions, and up to 11% of projected country GHG emissions to 2030. A sensitivity analysis also showed that despite the variation across three of the main variables affecting GHG’s emissions, the CCS-fNRB-LPG scenario remains the most effective and the high LPG penetration scenario remains the most unfavorable. The study helped to identify 200 high-priority municipalities (8% of total) located in the Center-South of Mexico encompassing 30% national FW consumption, 31% total FW users, and 55% of total GHG mitigation. In these high-priority counties a win–win policy in terms of social, health and environmental objectives may be achieved in the short-term, improving the efficacy of public policies related to GHG mitigation, universal access to clean energy, and sustainable development.
1. Introduction

Nowadays, 2.5 billion people — or about one third of the world’s population — rely on biomass to cook and to cover other essential household energy needs using traditional open fires — also known as three-stone fires (TSF) — (IEA 2017). The persistence of traditional biomass use is underpinned by its contribution to the world’s primary energy supply. Traditional biomass contributed with about 30 EJ — or roughly 60% of world’s total biomass contribution estimated at 50.2 EJ, and 6.1% of world’s total primary energy supply estimated at 492 EJ — in the year 2008 (Chum et al 2011). The use of biomass in TSF causes important health, environmental and socio-economic problems (Masera et al 2015). Replacing these TSF with clean woodburning stoves and fuels will allow advancing several sustainable development goals (SDG’s) such as SDG1 ‘No poverty’; SDG3 ‘Good health and well-being’; SDG7 ‘Affordable and clean energy’; and SDG13 Climate action (UN 2015). Efforts have been launched at the international level to spread the use of clean and efficient household cooking solutions to improve livelihoods, empower women, and protect the environment (GACC 2016). For example, the Global Alliance from Clean Cookstoves is promoting the adoption 100 million clean stoves by the year 2020.

Most interventions have concentrated on either disseminating improved woodburning cookstoves (ICS) or, increasingly, on promoting the exclusive use of clean fuels such as LPG. Evidence worldwide indicates that, very seldom, particularly in rural areas, are clean fuels such as LPG used exclusively (Masera et al 2015). On the contrary, the norm is substantial stacking of LPG with traditional devices. LPG also faces problems to reach the poorest and more remote households. An alternative that has not been examined in detail is the combined use of ICS with clean fuels. This last strategy assures, on the one hand, that the benefits of clean cooking may reach most rural households and at the same time, as the stacking with traditional fires is much reduced or even eliminated, the strategy maximizes health benefits for those households able to include LPG in their menu of cooking fuels.

Also, future scenarios have been developed that examine the GHG mitigation impacts of alternative ICS dissemination interventions. However, most of these efforts lack a spatial component. Their outcomes are presented in terms of aggregated national or regional data (see for example Cameron et al 2016). However, the specific ICS and clean fuels spatial dissemination strategies chosen play an important role because their carbon benefits are also spatially dependent. This is so because only when FW is extracted in a non-renewable manner net CO₂ emissions are released to the atmosphere. Therefore, it is only in regions where FW extraction is not sustainable (i.e. regions with high non-renewable fuelwood harvesting of fNRB) that ICS provides carbon dioxide emission reductions benefits. Thus, determining the fraction of FW unsustainable harvested, or fNRB, and its spatial distribution across the country is very important to prioritize ICS dissemination areas that will result in the largest mitigation of CO₂ emissions (Ghilardi et al 2007).

Black carbon and other short-lived climate pollutants such as CH₄ and CO have also attracted attention recently because of their contribution to global warming. Several studies have suggested that BC could be the second (Bond et al 2013) global climate modifier, just behind CO₂, and it could be even the most important in certain regions of the world (Jacobson 2000, Bachmann 2009, UNEP 2011). Additionally, BC can also affect human health since it is a component of particulate matter (Molina and Luis 2011, UNEP 2011). BC has also other collateral impacts on the environment, such as triggering changes on precipitation patterns and accelerating melting processes when it is deposited on ice surfaces, among others. Solid biomass used for cooking and heating is estimated to contribute globally around 25% of BC emissions (Lee et al 2013). For this reason, mitigating BC emissions through an efficient use of biomass and clean fuels could potentially reduce BC impacts on climate change, air quality, and human health in the short term (Bachmann 2009, UNEP 2011).

1.1. The Mexican context

Mexico provides a good example of the complexities associated with household energy transitions to cleaner fuels and devices. On the one hand, Mexico is a country with an emerging modern economy and a large industrial base. However, it is estimated that about 22.5 million people (or near 20% of Mexican total and 90% of rural population) still used fuelwood (FW) for cooking in open fires in 2010. Approximately 16.8 million people are exclusive users, and 5.7 million uses wood in combination with LPG (mixed use) to cover their cooking and other basic needs. Total fuelwood use reaches 310 PJ yr⁻¹ or 40% of total residential sector energy use (763 PJ) (SENER 2010, Serrano-Medrano et al 2014).

The use of fuelwood in TSF has been associated with a series of social, economic and environmental negative impacts in Mexico. For instance, Johnson et al (2009a) reported high GHGs emissions due to the use of TSF and to the unsustainable harvest of wood-fuel resources. Indoor air pollution levels in households using TSF surpass the levels recommended by the World Health Organization (WHO), and cause severe respiratory problems mainly to women and children (Armendáriz et al 2008, Romieu et al 2009, García-Frapolli et al 2010).

Historically, the Mexican government has tried to eliminate the use of fuelwood in TSF by promoting the penetration of LPG and, to a lesser extent, by implementing national woodburning ICS (improved
2. Methodology

2.1. Scenarios considered in this study

2.1.1. Business as usual scenario (BAU)

To develop the BAU scenario we used the model by Serrano-Medrano et al. (2014), which involves a spatially-explicit approach to assess the evolution of fuelwood use and national fuelwood consumption for the period 2014–2030. Total fuelwood annual consumption was estimated as the product of per capita consumption and saturation (percentage of users) times total population, considering stacking—i.e., by identifying exclusive fuelwood users and mixed fuelwood—LPG users. The model assumes that most fuelwood users cook with TSF. This is because, while there are initiatives to disseminate CCS, their impact has been limited so far. To account for the impact of these programs we assume that 340 thousand households use CCS throughout the modeling period. The analysis was conducted at the county (municipality) level, with a total of approximately 2500 units of analysis. Each county is modeled independently according with its own future population and to its specific FW and LPG users’ projection. For more details about the model refer to the supplementary material—appendix A is available online at stacks.iop.org/ERL/13/115004/mmedia—and to Serrano-Medrano et al. (2014). The projection of LPG users in the BAU scenario is dependent to the projection of FW mixed use.

2.1.2. Alternative scenarios

To reduce the impacts of traditional FW use, this study considered an ambitious substitution of TSF by CCS and LPG. Based on relevant criteria highlighted in the literature we initially considered six different policy scenarios involving the penetration of either CCS or LPG or both. The scenarios also differed in their spatial strategy targeting first, either counties with higher fNRB, higher number of exclusive FW users (EFWU) or higher number of mixed FW-LPG users (see supplementary material). The three more contrasting scenarios according to their outcomes were finally considered. The model was implemented using Matlab® and ArcGIS. The Alt1 scenario assumes a case where both CCS and LPG stoves (LPGS) are disseminated to replace TSF, which aims at understanding the impacts of a combined clean-fuel and improved-woodburning device strategy, which has been shown empirically to give the best results in terms of FW savings and in indoor air pollution reduction (Berrueta et al. 2008). Also, in this scenario, spatial projections give priority to counties with the highest levels of nonrenewable fuelwood harvesting (fNRB) to achieve the largest cumulative GHG emission mitigation. LPG is assumed to be adopted at a rate reaching 10% of EFWU per county per year in addition to the BAU scenario. This means that approximately 90% of all...
rural Mexican households would have an LPGS by 2030 (figure 1(b)). The Alt2 illustrate a case where only CCS are disseminated, giving priority to counties with the highest number of mixed FW users due to their increasing importance accordingly to the projections of FW users, and their potential larger impacts in terms of health benefits. In this case penetration of LPG continues in households at the historical rate, i.e., without assuming additional efforts regarding clean fuels. The Alt1 and Alt2 scenarios assume that 100% of dwellings using FW will have a CCS in 2030. This represents that about 5 million TSF will be replaced. Finally, the third alternative scenario (Alt3) was constructed assuming only LPGS are promoted in rural households at the same rate as in the Alt1 scenario. In this case, LPGS are assumed to be used in households together with TSF (i.e., no CCS are disseminated). As explained above, TSF users are of two types: (a) EFWU or mixed FW-LPG users (MFWU). Also, the alternative scenarios use the same socio-demographic projection as the BAU scenario and assume the same logistic penetration function. This logistic function was chosen as it is expected that the annual TSF replacement goals could be gradually increased as more CCS are disseminated.

2.2. Total fuel use
Total FW use in the BAU scenario is estimated as the product of per capita FW use times the number of users for each county. It is calculated separately for exclusive and mixed users for each year of the simulation, the country total is the sum of totals by county. Per capita FW use varies by vegetation type, a weighted average is estimated for each county according to the distribution of the different vegetation types.
present in its territory. Thus, for exclusive users, total county consumption is the average per capita use per county times the number of users in this county. The reduction of FW use associated with the switching from exclusive use to mixed LPG-FW use is highly variable in Mexico, with savings ranging from negligible to 50% (Masera y Navia 1997, Masera et al 2000). In this paper, we assumed that mixed users save 50% FW use with regards to exclusive users in all counties (see supplementary material for more details).

The per capita use of LPG is assumed to be of 0.10 Kg d$^{-1}$ throughout the country, which has been estimated by Masera y Navia (1997) and other studies. The model assumes that when rural residents adopt LPG, they always continue using FW; i.e. they become mixed FW-LPG users. This is a fact that has been widely documented in Mexico and is associated with the stacking patterns of fuel use common in Mexican rural households (Masera et al 2000).

The introduction of CCS is assumed to result in 50% of FW savings for both exclusive and mixed FW-LPG users. The adoption of CCS is not thought to change the consumption patterns of LPG. Total FW use in the alternative scenarios is therefore estimated adjusting the consumption obtained in the BAU by the number of households that adopt a CCS at each simulation year. The absolute amount of fuel savings that are obtained in each scenario at any time ‘$t$’ depends on the specific counties targeted for stove dissemination.

### 2.3. Total GHG emissions

For any given county, we estimate the total CO$_2$, net CO$_2$, CH$_4$, CO, and BC emissions, as well as CO$_2$ equivalent emissions associated with the use of TSF, CCS, and LPGS in the BAU and the alternative scenarios, as appropriate. To estimate net CO$_2$ emissions, we multiplied the CO$_2$ emission factor (EF) of FW burned in TSF and CCS by the county fraction of non-renewable biomass (fNRB) (see below). Equivalent-CO$_2$ emissions of CH$_4$, BC, and CO were estimated multiplying the emission factor of each gas per kilogram of FW per device (TSF or CCS) by its global warming potential. Total national emissions at any time ‘$t$’ are the sum of county emissions. Finally, the mitigation associated with any given scenario is the difference between the emissions in the BAU and the emissions in the specific scenario under analysis.

Mathematically, the emissions per county ‘$k$’ are

\[
\text{ECO}_{2t,\text{BAU}} = \sum_{k=1}^{n} \text{FWCCSC}_k + \text{ECO}_{2t,\text{CCSprevBAU}} + \text{ECO}_{2t,\text{LPGSBAU}},
\]

where

\[
\text{ECO}_{2t,\text{TSFBAU}} = \sum_{k=1}^{n} \text{FWTSFC}_k \times [(\text{EFTSFCO}_k \times \text{fNRB}_k) + (\text{EFTSFCCH}_k \times \text{GWP}_{244}) + (\text{EFTSFCBC}_k \times \text{GWP}_{44})] + (\text{EFTSFCO}_k \times \text{GWP}_{244})]
\]

and

\[
\text{ECO}_{2t,\text{TSFALT}} = \sum_{k=1}^{n} \text{FWTSFC}_k \times [(\text{EFTSFCO}_k \times \text{fNRB}_k) + (\text{EFTSFCCH}_k \times \text{GWP}_{244}) + (\text{EFTSFCBC}_k \times \text{GWP}_{44})]
\]

The emissions of the alternative scenarios are

\[
\text{ECO}_{2t,\text{ALT}} = \text{ECO}_{2t,\text{TSFALT}} + \text{ECO}_{2t,\text{CCSintro}} + \text{ECO}_{2t,\text{LPGSALT}},
\]

where

\[
\text{ECO}_{2t,\text{LPGSALT}} = \sum_{k=1}^{n} \text{LPGG}_k \times [(\text{EFLPGSCO}_k + (\text{EFLPGSCH}_k \times \text{GWP}_{244}) + (\text{EFLPGSBC}_k \times \text{GWP}_{44})] + (\text{EFLPGSCO}_k \times \text{GWP}_{244})]
\]

Finally, the mitigation associated with the alternative scenarios is

\[
\text{ECO}_{2t,\text{mitALT}} = (\text{ECO}_{2t,\text{BAU}}) - (\text{ECO}_{2t,\text{ALT}}).
\]

Finally, the cumulative mitigation associated with any alternative scenario ‘$t$’ is

\[
\text{ECO}_{2t,\text{mitcumALT}} = \sum_{t=2014}^{t=2030} \text{ECO}_{2t,\text{mitALT}},
\]

where

\[
\text{ECO}_{2t,\text{BAU}} \text{ and } \text{ECO}_{2t,\text{ALT}} \text{ are the total emissions of CO}_2 \text{ under the BAU and alternative scenarios respectively. } E_{\text{ECO}_{2t,\text{STFBAU}}}, E_{\text{ECO}_{2t,\text{CCSprevBAU}}}, \text{ and } E_{\text{ECO}_{2t,\text{LPGSBAU}}} \text{ are the total emissions of CO}_2 \text{ associated with TSF, CCS, and LPGS in use under the BAU scenario, respectively. } E_{\text{ECO}_{2t,\text{STFALT}}}, E_{\text{ECO}_{2t,\text{CCSprevALT}}}, \text{ and } E_{\text{ECO}_{2t,\text{LPGSALT}}} \text{ are the total emissions of CO}_2 \text{ associated with TSF, CCS, and LPGS in use under the alternative scenario ‘$t$’, respectively. FWTSFC}_k \text{ is FW total consumption associated with TSF in use per county ‘$k$’ for the specified scenario. FWCCSC}_k \text{ is FW total consumption associated}
\]
with CCS in use per county ‘k’ for the specified scenario. FW-LPGSC, is LPG total consumption associated with LPGs in use per county ‘k’ for the specified scenario. EFTSFCO₂, EFTSFCH₄, EFTSFBC, EFTSFSCO are the TSF emission factors of CO₂, CH₄, BC and CO respectively. EFCCSCO₂, EFCCSCH₄, EFCCSBC, ECCSCO are the CCS emission factors of CO₂, CH₄, BC and CO respectively. ECO₂,mitALT, is the annual mitigation associated with the alternative scenarios. CO₂,mitcumALT, is the cumulative mitigation associated with the alternative scenarios during the 2014–2030 period.

2.3.1. Net CO₂ emissions: fNRB estimation
When introducing CCS, CO₂ emissions derived from the use of TSF are only mitigated if FW is extracted in a non-renewable manner (i.e., if there are net CO₂ emissions to the atmosphere). To determine netCO₂ emissions, the fraction of unsustainable FW harvest, or fNRB and its spatial distribution by county is needed.

In this paper, we estimated fNRB at a county level using the Woodfuels Integrated Supply/Demand Overview mapping (WISDOM) a methodology developed by Masera et al (2006). WISDOM analyses demand and supply data regarding fuelwood use. The use of county-based fNRB values proposed in this study helps to more accurately estimate the actual amount of FW that is non-sustainably harvested. However, this exercise does not attempt to substitute local analyses required for small-scale carbon offsets projects (Johnson et al 2009a). The fraction of non-renewable fuelwood harvesting was done following the methodology described by Johnson et al (2009a). This fraction was obtained from the quantity of FW demand that exceeds the sustainable FW supply within each county. In this study, fuelwood supply only considers the amount of sustainably produced woody biomass that could be used for energy purposes for each vegetation type. Two important parameters that need to be estimated to obtain fNRB values are: (i) the productivity of aerial biomass by vegetation type, from which it was derived the amount of available FW supply; and (ii) the accessible forest area within each county. This parameter was estimated using a friction map in a GIS. The geographic features used to build the friction map were slope, roads, and rivers across the country. The FW balance considered that FW used within a given county only comes from the same county forest accessible areas. Protected areas were excluded from the analysis. Also, in absence of reliable future land-use change projections at the county level in Mexico, we assumed that the vegetation area in the base year remained constant. Therefore, fNRB was only affected by future projected FW consumption values. (See appendix C in the supplementary material for more details) and Serrano-Medrano (2016) A sensitivity analysis of fNRB values was also performed to obtain their impact on the mitigation values.

| Scenario         | CO₂ | CO | CH₄ | BC  |
|------------------|-----|----|-----|-----|
| Open fire        | 1533| 82 | 5.5 | 0.30|
| Improved cookstove | 1617| 19 | 1.0 | 0.10|
| LPG              | 3085| 15 | 0.05| 0.01|

GWP (100 year CO₂):

- CO₂: 1.0
- CH₄: 1.9
- BC: 28
- GWP: 460

Notes: GWP = global warming potential; BC = black carbon. For fossil methane, the GWP is 30. Emission factors estimated by Habib et al (2008), Smith et al (2000a, 2000b) for CO₂, CH₄, and CO were determined by chromatography with a flame ionizer detector (FID). Teflon filter samples were analyzed for black carbon (CN) content by reflectometry (Habib et al 2008 and Johnson et al 2008). The samples to determine emission factors correspond to household in rural communities that use FW for their daily cooking activities.

- "Refers to ‘U’ type cookstove in home. (Johnson et al 2008),
- "Refers to Brick Patsari stove in home. (Johnson et al 2008),
- "LPG stove. (Smith et al 2000b, 2000a, Habib et al 2008),
- "IPCC 2014.
- "IPCC 2007.
- "IPCC 2013.

2.3.2. GHG emission factors by type of stove
When burning FW to cook, in addition to CO₂, gases such as CH₄, CO, and BC derived from its incomplete combustion are also released contributing to increase GHG’s emissions. There are few measurements of GHG pollutant emissions from TSF and CCS in Mexico. Emission factors estimated by Johnson et al (2008) for CO₂, CH₄, CO, and for BC in Mexico were considered for this study. For LPG, we used the emission factors reported in the literature (table 1).

Emission factors for each device in grams of pollutant per kilogram dry fuelwood (g pollutant kg⁻¹) are reported in table 1. The emission factors can vary by region or country due to the type of fuel used, the type of stove and the local environmental factors. In the same way, the update of the GWP can cause differences in the CO₂, estimation and mitigation scenarios, for this study the most recent GWPs are considered.

Currently there is a great discussion about the contribution of organic carbon (OC) to global warming. OC contributes to cooling due to its negative GWP, but there is uncertainty in its estimation. Therefore, OC was excluded in this study.

2.4. Sensitivity analysis
A sensitivity analysis was conducted to show the impacts on cumulative emissions and GHG mitigation from changes in three main parameters: (a) per capita FW consumption; (b) CCS FW savings regarding traditional open fires; and (c) FW savings of Mixed FW-LPG users with regards to exclusive users. These three main parameters were increased or decreased by thirty percent. Additionally, an optimistic and pessimistic scenario analysis was also carried out. The
optimistic scenario simultaneously assumed a decrease of per capita FW consumption and an increase of both CCS FW savings and FW savings of mixed FW-LPG users by thirty percent with regards to the BAU assumptions. The pessimistic analysis assumes an increase of per capita FW consumption, and a decrease of both CCS FW savings and FW savings of mixed FW-LPG users by thirty percent.

3. Results

3.1. Evolution and spatial distribution of FW users

The BAU scenario predicts a very small reduction in the total number of FW users in Mexico, from 22.3 million in 2014 to 21.9 million in 2030; mixed users are expected to grow at the expense of exclusive users, passing from 5.7 million to 6.9 million within the same period (figure 1(a) and table 2). Most users are thought to continue relying on TSF. The national figures hide contrasting and many times complex dynamics at the county level: from counties with large absolute growth in FW users and those with large absolute reductions in their number, to counties with both growth and reductions in FW users during the simulation period (figure C.1 in appendix C in the supplementary material shows the evolution of FW exclusive users saturation for selected counties).

There is a marked geographic variation of the counties initially targeted for CCS dissemination, depending on each scenario’s priority criteria. Figure 2 depicts priority CCS dissemination counties to receive CCS before or in the year 2024. This year was selected because approximately 60% of CCS is assumed to have been disseminated, therefore high priority counties

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Table 2. Evolution of FW users and cumulative consumption in the BAU and the alternative scenarios.

| Scenario | FW users | FW cumulative consumption |
|----------|----------|----------------------------|
|          | Exclusive | Mixed | Total | Exclusive | Mixed | Total | Savings |
|          | 2014 | 2030 | 2014 | 2030 | 2030 | 2030 | 2030 | 2030 |
| BAU      | 16.4 | 15.3 | 5.9 | 6.7 | 22.3 | 22.0 | 257.4 | 51.6 | 309.0 | N.A. |
| Alt1 CCS FNRB LPGS | 16.4 | 3.1 | 5.9 | 18.9 | 113.1 | 84.6 | 197.7 | 111.3 |
| Alt2 CCS MIXED-USE | 16.4 | 15.3 | 5.9 | 6.7 | 187.9 | 35.0 | 222.9 | 86.1 |
| Alt3 LPGS | 16.4 | 3.1 | 5.9 | 18.9 | 132.2 | 116.0 | 248.2 | 60.7 |
could be detected. A total of 200 counties—comprising only 8% of total, 31% of FW users and 30% of total consumption—could be considered as high priority counties as they get selected irrespective of the scenario chosen. These counties are mainly located in the states of Veracruz, Puebla, State of Mexico, Chiapas, Michoacán, Tabasco, Oaxaca and Hidalgo (a list of the priority counties is available in the appendix D of the supplementary material).

3.2. Future projection of FW and LPG consumption
In the year 2030, FW consumption is expected to reach approximately 18.4 million tons of dry matter (MtDM) in the BAU scenario. Cumulative FW consumption in the BAU scenario was near 309 MtDM. Annual FW consumption is reduced by 36%, 28% and 20% in the Alt1, Alt2 and Alt3 respectively. Therefore, cumulative FW savings represented between 60 MtDM and 111.6 MtDM (see table 2).

3.3. Projection of GHG’s emissions
Figure 3 shows the projection of cumulative GHG emissions by gas and scenario from 2014 to 2030. Scenarios are ranked in terms of decreasing emissions. The BAU scenario shows the highest emissions with 364.3 MtCO2e. The Alt3 scenario is next with 313.9 MtCO2e. The CCS scenario targeting mixed users (Alt2) comes next with lower cumulative emissions. The Alt1 scenario achieves the lowest cumulative emissions. The share of each gas in total emissions also vary by scenario, with CO2 being slightly more dominant in the three alternative scenarios than in the BAU. In the former scenarios, up to 69% come from net CO2 emissions, while in BAU 37% are from non-CO2 gases.

Table 3 shows the contribution of each technology (TSF, CCS and LPGS) to total cumulative emissions by scenario. It is interesting to highlight that despite the fast penetration of LPGS and CCS assumed in the alternative scenarios, TSF continue to account for the largest share of cumulative emissions in all cases (from 63% to 88% depending on the scenario).

3.4. GHG mitigation and its spatial distribution
There are important differences in the absolute GHG mitigation attained in the scenarios as well as in its spatial distribution. The highest cumulative mitigation values for the period were obtained in the alternative scenario Alt1 (CCS-FNRB-LPGS) with 126.3 or 35% of BAU cumulative emissions (table 3). In contrast, the lowest cumulative mitigation was obtained in the LPGS scenario (Alt3), with only 50 MtCO2e (table 3;
see also figure 4 for the time evolution of the cumulative mitigation by scenario). The difference between the highest and lowest mitigation scenario reaches 60%.

The cumulative mitigation per county is very heterogeneous (see figure 5 for an illustration of the mitigation achieved in the alternative scenario Alt1 (CCS-fNRB-LPGS). The highest GHG’s emissions mitigation by county is found in the Mexican Southern states of Veracruz, Tabasco and Chiapas; in the Central Mexican Highlands (e.g. State of Mexico and the Purepecha Region in Michoacan), and in the Northwestern states of Sinaloa and Chihuahua.

3.5. Sensitivity analysis
Figure 6 shows that regardless the variation on the three main parameters, the Alt3 cumulative mitigation in 2030 is the lowest ranging from 7 to 91.7 MtCO2e. In contrast, the Alt1 cumulative mitigation is the highest ranging from 75.7 to 181 MtCO2e. The Alt2 cumulative mitigation varies from 71.7 to 148 MtCO2e.

4. Discussion
There is a large body of literature addressing the fuel savings, health and greenhouse mitigation implications of cookstove dissemination programs. There are also emerging spatial analyses and models that seek to understand where and how people harvest fuelwood and what are the associated environmental impacts (Adrian Ghilardi et al 2016). Bailis et al (2015) examines the impact of different cookstove
dissemination scenarios accordingly to priority goals such as climate change mitigation, decreasing dependence on non-renewable biomass (NRB), or reducing exposures to (HAP). However, by and large, studies addressing cookstove dissemination lack a spatial and fuel stacking component. To our knowledge, this article is the first country-level analysis of future scenarios to explicitly model the spatial implications of CCS and clean fuel programs derived from a set of specific public-policy criteria at a municipality (county) level. It is also novel in examining the spatial distribution of the GHG emissions and mitigation impacts associated with the different scenarios. Finally, the study is also innovative as it explicitly incorporates fuel and device stacking in the future mix of alternative cooking technology options. This feature allows, among other things, tracking the impacts in terms of emissions and mitigation by fuel and device.

Regarding the BAU scenario, which was constructed using in-depth case studies, historic trends in fuel-use patterns as well as official county-wise demographic projections, our study suggest that unless there is a strong policy change in both current programs to promote LPG and CCS, the number of TSF fuelwood users and the associated GHG emissions will continue to be very high until the year 2030. In fact, despite the expected increase in the number of mixed FW-LPG users, due to stacking of LPGS and TSF, GHG emissions and wood consumption will not decrease substantively, nor the IAP and other burdens associated with the use of traditional fires for cooking.

We also found that there are important differences in the cumulative mitigation achieved by different policy strategies. Specifically, there are differences between policies centered in the promotion of clean fuels alone and those policies aiming at the dissemination of biomass CCS. We found that if substantive stacking of LPG with TSF continues in the future—as has been the norm in rural Mexico for the last 40 years—promoting a high penetration of LPG alone will result in the lowest GHG mitigation gains (60% lower than the best-case). On the other hand, when LPG is promoted together with CCS, the best results are achieved, with a 35% savings with regards to the BAU. This result highlights the importance of integrating interventions and policies (i.e., by working simultaneously to ‘making the clean available’ and ‘making the available clean’ (Smith and Sagar 2014), rather than undertaking each strategy in isolation.

Approximately 49%–57% of total mitigation is achieved by CO$_2$, depending on the scenarios, with the rest evenly distributed among the other non-CO$_2$ gases (CO, CH$_4$, and BC). The scenarios results suggest that the cumulative effect of TSF in GHG emissions mitigation is very difficult to remove. Even assuming optimistic CCS and LPGS penetration rates, these devices are so pollutant that they continue to account for most of the emissions in all alternative scenarios (see table 3. Cumulative emissions contribution by stove type). This again, illustrates the importance of assuring the complete replacement of TSF by CCS and LPGS, and to have aggressive clean stove dissemination programs from the start. However, this last objective is difficult to attain, as experience shows that usually a learning period is needed before reaching massive dissemination. Also, if TSF are to be removed effectively, stove programs will need to have extensive user feedback and be sensitive to the diverse needs satisfied by the traditional fires in different regions (Ruiz-Mercado and Masera 2015).

The sensitivity analysis showed that despite the large variation imposed on selected key model parameters, the Alternative scenario 1 remained the most favorable in terms of the mitigation of CO2e emissions. On the contrary, the Alternative scenario 3 (Alt3), resulted in the less favorable option. Even under the ‘optimistic’ variation of the selected parameters, the Alt3 cumulative mitigation value was only near 50% of the Alt1.

Regarding the effectiveness of alternative CCS-scenarios, we found that prioritizing stove dissemination...
in the highest fNRB counties early within the period of analysis (i.e., prioritizing the reduction of cumulative GHG emissions) was about 15% more effective than emphasizing counties with the higher number of mixed FW users. The analysis also shows that areas were FW use is high may not have always an important impact on GHG’s emission mitigation, because FW supply in these areas may not be under extraction stress (i.e., they have a low fNRB value). For instance, only 43% of the top one hundred counties with the highest cumulative mitigation are also within the top one hundred counties with the highest cumulative FW consumption.

The spatial analysis presented here may constitute a helpful tool for identifying priority areas for clean stoves and fuels dissemination. We have found that the overall national trend regarding the evolution of FW users and other parameters hide important and contrasting regional differences: from areas with few and rapidly decreasing users to those where an important increase of users is still to be expected in the mid-term; or from areas where exclusive FW use is very extended to other areas where mixed users are largely dominant. These differences in FW use dynamics need to be acknowledged to design regional specific government programs and incentives for clean stove and fuel dissemination. This analysis could also be implemented together with social network analysis regarding diffusion of CCS to increase the probability of CCS programs success (Ramirez et al 2014).

A key finding of this study is the identification of 200 high-priority municipalities for clean stoves and fuel dissemination. These counties, representing only 8% of total, nonetheless account for 30% national FW consumption, 31% total FW users, and 55% of total GHG mitigation. High-priority counties are places where a win–win policy in terms of social, health and environmental objectives may be achieved in the short-term.

Finally, it is worth noting that as part of the Paris Agreement on Climate Change, Mexico has committed to reduce their national GHG emissions by 22% and their BC emissions by 51% in the year 2030 (UNFCCC 2015). Achieving these targets will not be easy taking into account that Mexico currently relies on fossil fuels for 90% of its domestic energy demand (BNE 2016). Under these circumstances, the dissemination of clean cookstoves together with clean fuels in rural Mexico to replace TSF may represent a viable and cost-effective alternative to contribute to the country’s future emission reduction targets.

Several factors affect the results from this study. To begin with, GHG emission factors for TSF and CCS are still highly uncertain, particularly regarding BC and non-CO₂ gases, as only few measurements have been conducted in Mexico. Including OC emission factors may also change the climate benefits from replacing TSF with CCS, but no reliable estimates of this parameter exist at present. fNRB values are also difficult to estimate and have a strong influence in the net CO₂ emissions from FW harvesting. The assumed CCS and LPG penetration rates and their time dynamics are also important factors determining the overall mitigation achieved in the scenarios. Also, the scenarios assume that switching to LPG leads to substantive FW savings, which is not always the case according to existing field studies (Masera et al 2000, Berrueta et al 2008, Miranda 2015). If fewer FW savings from adopting LPG are achieved, the LPG-alone scenario will look even less attractive from a GHG mitigation perspective. On the other hand, we have assumed that well designed CCS stoves and dissemination programs lead to negligible stacking of these stoves with TSF. If this were not the case, then the relative gains from CCS will also look much less attractive.

5. Conclusions

Our analysis aimed at examining the GHG implications of country-wide alternative scenarios portraying contrasting technology adoption dynamics and spatial patterns of CCS and clean fuels dissemination. We hope that this will provide guidance to policy makers in both understanding the trade-offs (or synergies) between different social and environmental sustainable development objectives, and developing better targeted and thus more cost-effective clean stove dissemination strategies in rural Mexico. A county-based spatial-temporal model was developed to determine the impact, in terms of mitigation of GHG’s, derived from implementing clean technologies following different geographic dissemination strategies.

We would like to highlight three main findings. First, large GHG emissions savings could be obtained by replacing TSF with clean-stove and fuels in rural Mexico. Cumulative savings amount to 17% of net total annual Mexican emissions in 2010 estimated at 748 MtCO₂ (INECC 2013) or 11% of projected country emissions to 2030 by Johnson et al (2009b).

Second, we observed that the maximum mitigation is obtained by an integrated policy strategy that promotes simultaneously a cleaner and more efficient use of FW with CCS together with the use of LPG. Existing field studies in Mexico show that—as exclusive LPG use has been very hard to achieve so far in Mexican rural homes—the combination of LPG with CCS also brings the largest health benefits. From the total mitigation, approximately 70% comes from CO₂ and BC.

And third, this analysis also helps identifying a set of 200 priority counties (8% of total) which result selected early in each dissemination scenario irrespective of the priority criteria. These counties constitute areas where important synergies exist between public health, poverty release and environmental objectives, and should thus be key targets for dissemination of clean fuels and stoves.
The limitations of the present study are worth noting. Using fixed INRB values at the county level for the whole simulation period does not allow to account for the effect of FW harvesting on future deforestation patterns or patterns of forest regrowth. Due to data limitations, it was possible to model only one type of Mexican CCS. The emission factors for gases other than CO₂ and CO are very scarce and highly uncertain. Also, the FW savings associated with the implementation of CCS on FW-exclusive and mixed FW-LPG users come from a few existing studies in the Central Highlands of Mexico. Only one logistic function was assumed for all the dissemination scenarios. Finally, while we restricted our analysis of clean fuels to LPG, it should be noted that LPG is a fossil fuel with many environmental problems. Future work should examine other modern renewable fuels such as solar energy—including biofuels—that are more sustainable and could replace LPG in the mid-term.

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ORCID iDs

M Serrano-Medrano @ https://orcid.org/0000-0003-1776-5555

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