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Fuelwood use patterns in Rural Mexico: a critique to the conventional energy transition model

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KEYWORDS: **fuelwood, stacking model, energy transitions, greenhouse gases.**

JEL CODES: **N56, N76, Q41, Q42.**

This article presents an historical account of patterns of household fuelwood use in Mexico from 1960 until the present. The results of scenarios outlining the likely evolution of future fuelwood use according to different socio-demographic and technological variables are offered up to 2030 along with the expected environmental impacts. Mexico is an interesting case as it went from importing oil to becoming an oil-exporting country during the historical period under analysis and the use of liquefied petroleum gas (LPG) intensified in the residential sector. However, rather than exhibiting a sharp decline in fuelwood use, as would be expected from the energy transition model, we observe that fuelwood use has remained almost constant for more than 40 years. In fact, rather than completely switching to LPG, a large portion of rural and small-town households adopted a fuel-stacking strategy, combining both fuels on a long-term basis. We conclude by examining the implications of the current patterns of fuelwood use and fuel-stacking in terms of future fuelwood consumption, numbers of users and emissions of greenhouse gases.

Patrones del consumo de leña en el México rural: una crítica al modelo tradicional de transición energética

PALABRAS CLAVE: **leña, modelo de uso múltiple de combustibles, transición energética, gases efecto invernadero.**

CÓDIGOS JEL: **N56, N76, Q41, Q42.**

Este artículo presenta un repaso histórico a las pautas de consumo de leña en los hogares mexicanos entre 1960 y la actualidad. Muestra también algunas proyecciones de consumo hasta el año 2030 calculadas en función de algunas variables sociodemográficas y tecnológicas, y se estiman sus posibles impactos ambientales. El caso de México tiene interés ya que el país pasó durante el periodo analizado de ser importador de petróleo a ser exportador de ese recurso energético, al mismo tiempo que el consumo de gas licuado de petróleo (LPG) se intensificaba en los hogares. Pese a ello, en lugar de producirse una caída brusca en el consumo de leña como predice el modelo tradicional de transición energética, observamos que dicho consumo se ha mantenido bastante estable durante los últimos cuarenta años. De hecho, una parte muy considerable de los hogares rurales y de las pequeñas ciudades, en lugar de saltar al uso de LPG, han adoptado una estrategia de uso múltiple que combina el uso de ambos combustibles en el largo plazo. El artículo termina analizando las implicaciones de los patrones de uso de la leña y de la estrategia de su uso múltiple para el futuro, en términos de consumo, de número de usuarios y de emisiones de gases de efecto invernadero.

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1. INTRODUCTION

1.1. Global overview of fuelwood use and patterns

Approximately 2.6 billion people in the world currently use fuelwood (FW) and charcoal, as their principal energy source. Globally, these two woodfuels account for 10% of primary energy or 50.5 EJ. Of this figure, about 31 EJ are used mostly in open fires and rustic traditional stoves to mainly cover needs such as cooking and heating in the poorest households of developing countries. People relying on fuelwood are mainly located in Asia, India, Sub-Saharan Africa, Indonesia and Latin America where users account for 37%, 28%, 22%, 6% and 2% of the total users, respectively (Chum *et al.*, 2011).

Reliance on FW has positive and negative impacts. On the positive side, FW is a potentially renewable energy source, it is locally available in most circumstances and it represents zero monetary cost for those families collecting the fuel. Fuelwood can come as a byproduct of other activities such as agriculture or forestry. When conducted on a sustainable basis, harvesting FW from natural forests reduces the incidence of fires and pests. Traditional devices –such as three-stone fires– are well adapted to the local needs and often represent zero monetary cost. FW use is also a fundamental social activity among women in rural areas because while sometimes other family members could also gather FW, only women carried out cooking tasks.

On the negative side, harmful particles and gases are released when FW is burned in traditional open fires and they severely affect FW users` health as well as the local and global environment. Particularly, FW smoke has been related to several health problems that increase the mortality rates or disease causes (Bruce *et al.*, 2006; Naeher *et al.*, 2007; Pérez Padilla, Schilmann & Riojas, 2010; Torres *et al.*, 2008). FW smoke is also classified as a possible carcinogen agent by the International Agency for Research on Cancer (IARC) (Straif *et al.*, 2006). Health problems derived from FW smoke exposition range from difficulty to breath and acute respiratory illness that could lead to premature deaths mainly in women and children. Under a sustainable extraction pattern, emissions of carbon dioxide or CO2 derived from FW combustion are considered zero (also named *neutral*), that is the CO2 emitted when the wood is burned is re-captured by re-growing trees through photosynthesis. Nevertheless, when FW is burned in traditional devices an incomplete combustion occurs and other powerful greenhouse gases and pollutants such as methane (CH4), nitrogen dioxide (NO2), and carbon monoxide (CO) are released. Black carbon is also emitted during incomplete combustion of fuelwood. Therefore, traditional fuelwood use could also contribute to climate change (Arora, Jain & Sachdeva, 2013; Johnson *et al.*, 2008; Johnson, Edwards &

Masera, 2010; Preble *et al.*, 2014; Roden *et al.*, 2009; Schauer *et al.*, 2001; Shen *et al.*, 2013a, 2013b, 2014).

Understanding the evolution of FW use and its environmental impacts has proved a challenging goal. Different models have been proposed to explain FW use dynamics in developing countries. The fuelwood gap model was the first attempt to describe FW demand and supply relationships. This model predicted a severe FW energy crisis resulting from a combination of a growing population reliant on firewood and a depletion of FW supply due to an increasing deforestation (Openshaw, 1974, 1978; Eckholm, 1975). However, this crisis –to the extent predicted by the model– never occurred. Later, the *energy ladder model* (also known as the *energy transition* or *fuel switching model*) described how people relying on FW to cover their main energy needs could rapidly switch from "traditional" fuels –at the bottom of the ladder– to "modern" fuels –at the top of the ladder– such as LPG as soon as the household income increased (Baldwin, 1987; Smith, 1987; Hosier & Dowd, 1988; Leach & Mearns, 1988; Leach, 1992). This model has failed to explain residential fuel transitions in developing countries, very particularly within rural and peri-urban areas.

Masera, Saatkamp and Kammen (2000) proposed an alternative model to the fuel switching approach. This model explains that rather than switching linearly and permanently from traditional to modern fuels, people stack different fuels to cover their energy needs according to the tasks each fuel performs the best. Stacking also provides households with more flexibility and reliability in case of shortages of modern fuels. LPG and other modern stoves are also not well adapted to local cooking practices (such as making *tortillas* in Central America or *njeras* in Ethiopia). Fuel stacking patterns have prevailed despite many governments have launched active policies to boost the use of modern fuels (Masera *et al.*, 2015). Furthermore, the probability that this stacking pattern continues in the mid-term is high as projections highlight that near two billion people are going to still relay on FW in the year 2040 (IEA, 2016).

Additionally, examining the spatial distribution of FW users –and their related impacts– is also very important because FW use patterns are very heterogeneous and highly dependent on geographic variables (Ghilardi, Guerrero & Masera, 2007, 2009; Masera, Drigo & Trossero, 2003; Masera *et al.*, 2006). Spatially explicit and multi-temporal FW models are needed to better understand FW use dynamics at the household level. Recent developments in this area include Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) and Modeling Fuelwood Saving Scenarios (MoFuSS) models, which have been applied in several regions of the world and at different geographic scales –from pantropical to landscape level analysis (*e.g.* Bailis *et al.*, 2015; Ghilardi, Tarter & Bailis, 2018).

WISDOM is a spatial-explicit method for highlighting and determining priority areas of intervention and supporting wood energy/bioenergy planning and policy formulation. WISDOM supports strategic planning and policy formulation, through the spatial integration and analysis of existing demand- and supply-related information and indicators, and by modeling access patterns to supply sources. It provides relative/qualitative values such as risk zoning or criticality ranking, highlighting, at the highest possible spatial detail, the areas deserving urgent attention and, if needed, additional data collection. In other words, WISDOM serves as an assessing and strategic planning tool to identify priority places for action. WISDOM is a spatial, non-temporal model, meaning that applies geoprocessing operations such as proximity, overlay, or cumulative cost, *i.e.*, beyond maps of administrative units depicting data from a table, but lacking any temporal dynamics (Masera *et al.*, 2006).

MoFuSS is an open-source freeware developed to evaluate potential impacts of firewood harvest and charcoal production over the landscape. It's a GIS-based model that simulates the spatio-temporal effect of woodfuel harvesting on the landscape vegetation and that accounts for savings in non-renewable woody biomass from reduced consumption. MoFuSS is a spatiotemporal model, meaning that incorporates both spatial dynamics and geoprocessing operations (Ghilardi *et al.*, 2016).

In Mexico, FW is the main energy source in the rural sector, and accounts for almost 40% of total residential energy consumption in the country. Economic and environmental accessibility, as well as social and cultural factors play an important role in the persistence of FW use. Fuelwood users accounted 22.5 million and FW consumption reached 19.4 million tons of dry matter (MtDM) in 2010. Liquefied petroleum gas (LPG) is the other main fuel in the residential sector in the country. Penetration of LPG has been steadily increasing in rural areas, largely as a complement rather than a substitute to FW. Several projections have estimated that FW use will remain the dominant rural cooking fuel in the short and middle term in Mexico (Diaz, 2000; Serrano *et al.*, 2014).

In this study, we examined the historical evolution and implications of FW consumption in Mexico from 1960 to the present. We first review the different theoretical approaches that have been used to explain FW use dynamics in developing countries. We then use Mexico as a case study. We argue that in Mexico, energy transitions at the household level have followed a multiple fuel use pattern, where an increasing adoption of LPG has not displaced but mostly complemented FW use. We also present future scenarios of FW use assuming different socio-demographic and technological variables. We conclude the paper examining the implications of the current patterns of fuelwood use in the future in terms of fuelwood consumption, numbers of users and emissions of greenhouse gases.

1.2. Theoretical approaches to energy transitions in the residential sector

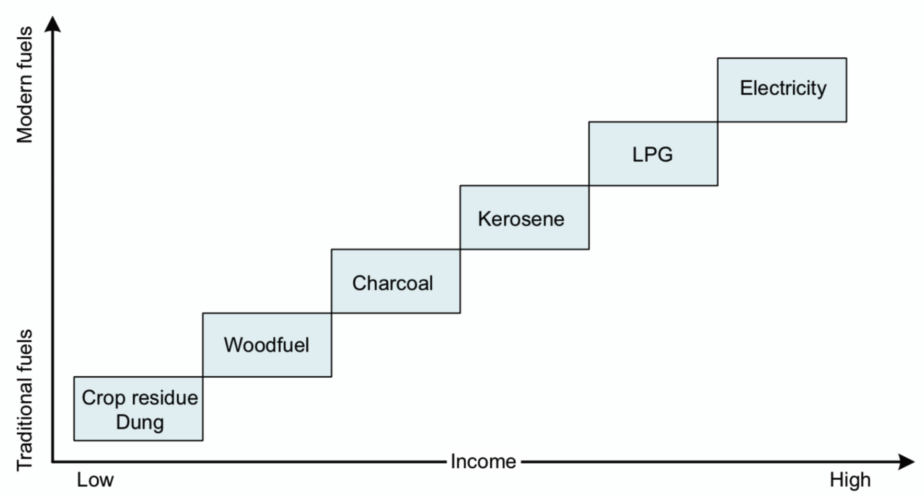
1.2.1. Fuelwood Gap model

During the 1970's a firewood energy crisis was predicted assuming that reliance on fuelwood by an increasing population would rapidly deplete the available forests. Plantations had to be established to avoid a major ecological disaster (Openshaw, 1974, 1978; Eckholm, 1975). Even global institutions such as the Food and Agricultural Organization (FAO) and the World Bank relied on these assumptions (Eberhard, 1992). The fuelwood energy crisis was modeled as the gap between sustainable fuelwood supply and demand. This gap was estimated to increase along with population growth. For some regions in Africa, the fuelwood gap model predicted a total devastation of the fuelwood stock within 5 to 30 years. These predictions motivated large- policy interventions to decrease this gap. Considerable afforestation or demand driven measures by dissemination of efficient cookstoves were the most common elections to reinstate the balance (Eberhard, 1992). However, the studies supporting a general energy crisis fail to account for fuelwood use resilience by means of regrowth or that people managed tree growing to cope with fuelwood scarcity (Leach & Mearns, 1988; Bailis *et al.*, 2015). As a result, recent studies suggested that woodfuel sustainability depends on local factors that are generally dismissed when using aggregated data and therefore they highlight the heterogeneous nature of fuelwood surpluses or deficits across regions (Eberhard, 1992; Bailis *et al.*, 2015).

1.2.2. Energy ladder model

Energy use in the residential sector was explained early by the energy ladder model (Figure 1). This model sought to explain household decisions when substituting or switching between fuels at a household level by means of socioeconomic status (Baldwin, 1987; Smith, 1987; Hosier & Dowd, 1988; Leach & Mearns, 1988; Leach, 1992). The model assumes that as a household income increases, people "naturally" abandon dirty, less costly fuel such as dung, charcoal or fuelwood –bottom of the energy ladder– and opt for "modern" fuels that are "cleaner", more expensive and less pollutant such as LPG –top of the energy ladder– (Smith, 1987; Hosier & Dowd, 1988). The rationale behind this model was that the transition from the bottom to the top of the energy ladder responded not only to pursue energy efficiency or to decrease indoor air pollution but also to gain status. As modern fuels are also used by means of "advanced" technologies, families desire to move up the ladder to demonstrate prosperity (Masera, Saatkamp & Kammen, 2000). Nevertheless, this model fails to explain observed dominant households' decisions such as combining (*i.e.* stacking) different fuels options according to certain cooking tasks or to ensure coverage of households' energy needs and, therefore, only changing partially to modern fuels (Masera & Navia, 1997; Masera, Saatkamp & Kammen, 2000; Masera *et al.*, 2015). The energy ladder model has proven insufficient to describe household energy transitions in rural areas where economic, and even cultural aspects need to be addressed to understand energy dynamics (Masera, 1993; Masera & Navia, 1997; Masera, Saatkamp & Kammen, 2000; Masera *et al.*, 2015). This approach has even been limited while explaining energy transitions in urban areas of developing countries (Hiemstra-van der Horst & Hovorka, 2008).

FIGURE 1
The classic energy ladder diagram

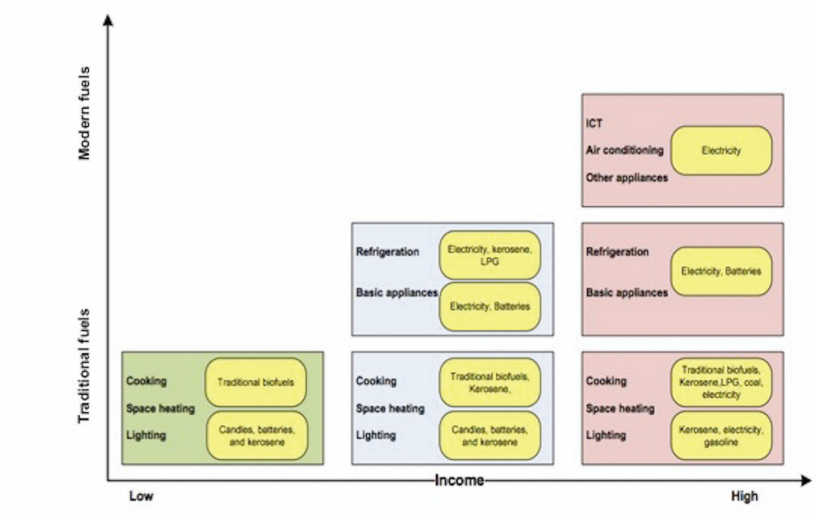


Source: Kowsari and Zerriffi (2011: 7505-17).

1.2.3. Fuel stacking model

As a response to the energy ladder failure to describe household energy transitions, Masera, Saatkamp and Kammen (2000) proposed an alternative approach, the *multiple fuel model* (Figure 2), to explain fuel use dynamics in the residential sector after conducting a longitudinal study in one village and analyzing data from a large- scale survey in four states in Mexico. This study showed that a fuel stacking approach better described actual household fuel use dynamics. The proposed model also encompassed previous observed patterns of multiple fuel use in other countries (Evans, 1987; Leach & Mearns, 1988; Fitzgerald, Barnes & McGranahan, 1990). It has been increasingly documented that a multiple fuel use strategy is more common than rare in developing countries, and not necessarily a short-term transitional stage but a rather mid to long-term strategy[1]. A multiple fuel model is able to describe the stacking behavior within the process of fuel use decision-making among households. It recognizes that the adoption of modern fuels is a complex process where economic, social and cultural aspects interact, rather than simply a change from one cooking fuel to another. Furthermore, inter-fuel substitution not only depends on decisions at the household level but also on the macroeconomic context and policies at the national level, like investment in roads or establishment of subsidies to purchase modern fuels like LPG. Once a household overcome the LPG stove investment, other barriers to maintain a steady use of LPG are likely to arise. With the LPG purchase, families very often build even a new kitchen and all the furnishing and cookware that this involves. These barriers together with income variability in rural households, position LPG adoption as a complex process taking place mostly in mid- high or high-income families in the communities (Masera, Saatkamp & Kammen, 2000). The multiple or stacking fuel model better adapts under the vast variety of circumstances existing in most rural and suburban areas of developing countries (Masera, Saatkamp & Kammen, 2000)[2].

FIGURE 2
Energy stacking diagram



Note: ICT is information and communication technology.
Source: Kowsari and Zerriffi (2011: 7505-17), adopted from IEA (2002).

1. See a review of examples in MASERA *et al.* (2015), SOUSSAN, O'KEEFE and MUNSLOW (1990), DAVIS (1995), and ALBERTS, MOREIRA and PÉREZ (1997).

2. See also MASERA *et al.* (2015) for a more detailed explanation of the fuel stacking process, including its rationale, patterns and health and environmental implications.

2. FUELWOOD USE PATTERNS IN MEXICO

2.1. Characteristics and evolution of the Mexican rural sector, 1960-2010

The Mexican rural sector is highly diverse regarding its economic, socio-cultural and ecological characteristics. Rural population lives in more than 196,000 localities, which shows the high level of dispersion existing in this sector. Most rural communities still lack infrastructure and services since economic development policies have usually favored industrial and urban sectors. Rural living conditions are in many cases insufficient to provide rural population the opportunity to overcome poverty. Poverty has remained as an enduring characteristic of rural population (OECD, 2009). As a result, many people have migrated from villages to urban centers. Seasonal and permanent migration to the United States has been very important too.

During the period of analysis rural demographics have changed considerably. In 1960, rural population was estimated at 17.2 million people living in 3.3 million households versus 23.3 million people (3.9 million households) in 1990 and 24.8 million people (6.3 million households) in 2010. Rural population has increased in absolute figures during the 1960-2010 period, but the share of people living in rural areas with respect to total population has decreased from 49.3% in 1960 to 22.2% in 2010. Family size in this sector has shrunk from 5.2 to 3.9 members in 1960 and 2010, respectively, resulting in a faster increase of the rural housing stock relative to that of absolute rural population.

Lustig and Székely (1997) found that moderate and extreme poverty are systematically concentrated in rural Mexican communities. Furthermore, these authors found that the concentration of extreme poverty in rural areas is higher than in urban centers, a trend that holds up to the present.

2.2. General characteristics of the Mexican rural sector, 1960-2010

2.2.1. Organization and land tenure

The Agrarian Reform that took place as a result of the Mexican Revolution (fist quarter of the 20th Century) is a key feature to understand the agrarian history of Mexico. Three main forms of land tenure were established: private, public and social –the social property was subdivided in communal land and *ejidos* (Minutti Lavazzi, 2007). *Ejidos* were created to empower peasants, by eliminating huge private extensions of land known as *latifundios*. *Ejido* members (or *ejidatarios*) were given the right to own and cultivate the land but not to sell it; also, *ejidos* were given representation at a federal level, and also were assisted in terms of technology and credits (Gordillo, Janvry & Sadoulet, 1998). After the Cardenista period in 1940, near 50% of the agricultural land had been converted to *ejidos*. The agricultural production of the *ejidos* increased from 11% in 1930 to 53% of the total in 1940 (Gómez Oliver, 1996). However, after the government of President Lázaro Cárdenas, incentives to *ejidos* decreased gradually as agricultural policies of subsequent governments were oriented to empower the agrarian private sector. Since the 1990s, a decided "counter- agrarian reform" has taken place in Mexico as a result of neoliberal policies favoring the privatization of land. The process initiated in 1991 when President Carlos Salinas de Gortari announced a constitutional reform that legally allowed *ejidos* peasants to sell their land (Medina, 2006).

2.2.2. Subsistence versus commercial agriculture

The agriculture sector in Mexico is very heterogeneous across the territory. There are sharp and increasing contrasts between a large number of subsistence small-scale farmers and a commercial –mostly export oriented– sector. In the Central and Southern regions, the agriculture sector remains mostly traditional (*i.e.* subsistence agriculture). Peasants generally depend on rainfed agriculture, cultivate maize and other staple food, mechanization is low and, produce mostly for self-consumption. On the contrary, the agriculture in the Northern region of the country, and within irrigated areas, is generally commercial with conspicuous mechanization and intensive use fertilizers and pesticides. This pattern has remained since the 60's and intensified after the signature of the Free Trade Agreement with the United States in 1994 (Minutti Lavazzi, 2007). The main crops cultivated in the Northern part of the country are cereals, tomatoes, vegetables for export, and sugar cane while in the Southern region the corn –as the base of the Mexican diet– is the most important crop, although tropical crops are also important.

3. METHODS

3.1. Estimation of fuelwood consumption

FW use evolution for the 1960-90 period was estimated from previous work by Masera (1993) and Díaz (2000) at national and state levels, respectively. For the 1990-2010 period and the projection 2010-30, a model was constructed at a county or municipality level (Serrano *et al.*, 2014).

Total FW consumption (FWTC) was estimated considering both exclusive and mixed FW-LPG users to align with the fuel-stacking patterns observed in Mexican rural households.

A bottom up model was used to determine exclusive and mixed FW consumption as follows.

$$FWTC = \sum_{k=1}^{n} FWC_{Ek} + FWC_{k}$$

Where FWTC is total fuelwood consumption in tones of dry matter per year (tDM/year), FWCEk is exclusive fuelwood consumption per county k, and FWCMk is the fuelwood when used in combination with LPG consumption per county k.

Annual FW consumption by county for both types of FW users was estimated as the product of FW per capita consumption (Cpc), saturation of FW users (S) and population. A total of 2,500 counties were analyzed. Saturation of FW users per county was obtained based on the National Bureau of Statistics (INEGI) census data. Data regarding which fuel was used to cook in dwellings, population, and average inhabitants per dwelling were used to estimate the number of FW users. By saturation of FW users per county we mean the proportion of FW users against total population within each municipality. The estimated saturation of FW users per county and per year (with values ranging from 0% to 100%) is multiplied by the total population at that given year and county in order to obtain the total number of FW users. The model assumed that people using FW to cook was a good proxy variable to estimated household FW use since Díaz (2000) found that more than 90% of residential FW use in Mexico is for cooking. Saturation of FW mixed users per county was estimated a function of FW exclusive saturation.

Average per capita fuelwood consumption for each of the five main ecological regions was estimated by means of an exhaustive literature review (Díaz, 2000; Masera & Navia, 1997; Puentes, 2002; Sánchez González, 1993; Tovar, 2004). Average per capita consumption ranges between 1.X and 3.0 kg/day, which are consistent with values reported for other Central American countries (Wang *et al.*, 2013). These five average values were assigned to the counties depending on their location within each ecological region using geographic information systems (GIS). Minimum average temperatures were also used to adjust these values. In other words, an additional factor was applied to FW consumption to increase its value within counties located in cold regions. These counties were identified using a GIS. Per capita FW consumption of mixed users was assumed optimistically to be half of FW exclusive per capita consumption (Ghilardi, Guerrero & Masera, 2009). There is not a large data base on actual FW savings of mixed FW users with regards to exclusive users. Existing estimates have a large variability, ranging from negligible to 50% or more (see Masera & Navia, 1997; Masera, Saatkamp & Kammen, 2000). In this study we chose a 50% value in order to have an estimate of the potential savings to be achieved by the adoption of clean devices such as LPG stoves.

In order to project FW consumption values to the year 2030 using the per capita values and saturation of both, exclusive and mixed, users previously explained, a business as usual scenario (BAU) was constructed[3]. The main assumptions were: a) per capita consumption values remain fixed because without additional measures, no significant technological change in the traditional devices used for cooking is expected –this is, three stone fires (TSF) are assumed to continue to be used during the entire period of analysis–; and b) FW saturation change following annual growth rates derived from 1990 and 2000 Census Data. The model also assumed population values from census data and from the National Population Bureau projections figures (CONAPO, 2012).

4. RESULTS

4.1. Historic and expected future residential fuelwood use patterns in Mexico, 1960-2030

4.1.1. Fuelwood users 1960-2030

The number of estimated total FW users for the 1960-2010 period is shown in Table 1. In 1960, the number of exclusive users reached about 22.62 million and about 1.1 million for mixed users. Mixed users were located principally in the urban sector. From then on, there has been a slight decrease in the number of total FW users, composed by a decrease in exclusive users and a six-fold increase of mixed FW-LPG users. This trend is expected to continue up to 2030, where we estimate that FW exclusive and mixed users will reach near 15.3 and 6.7 million in the year 2030, respectively[4].

3. A detailed information of the methods used is found in Serrano *et al.* (2014).

4. In addition to the consumption of FW in the residential sector, there is a considerable consumption of FW for process heating in small industries (*e.g.* brick makers, *mezcal* distilleries, bakeries, pottery makers, among others). FW consumption in this sector reaches 1.9 MtDM (or 28 PJ) (Tauro, Serrano & Masera, 2018).

4.1.2. Fuelwood consumption 1960-2030[5]

In 1960, total FW consumption reached about 19.5 million tons of dry matter (MtDM). In this year, exclusive and mixed consumption accounted for 18.9 and 0.7 MtDM, respectively. By 2010 total FW use had reached 19.74 MtDM. FW exclusive and mixed consumption were projected to reach near 15.1 and 3.32 MtDM in the year 2030, respectively. FW total consumption is expected to decrease slightly from 19.53 MtDM in 1990 to 18.42 MtDM in 2030.

It is interesting to note that official figures have routinely underestimated the amount of FW consumed in Mexico. Estimates from the Environmental Ministry (SEMARNAT) only account for the wood that is reported in the "formal system", that is, the wood that is harvested with management plans, and is recorded and taxed. However, this is less than 20% of total FW used, or a 5-fold underestimate of actual use.

TABLE 1

Fuelwood users and consumption, 1960-2030

Year	Exclusive users	Mixed users	Total users	Exclusive use	Mixed use	Total use
		(Million)			(MtDM/year)	
1960	22.62	1.09	23.71	18.85	0.70	19.55
1970	21.52	2.11	23.63	18.57	1.13	19.70
1980	19.86	3.10	22.96	18.20	1.57	19.77
1990	18.01	3.73	21.73	17.70	1.83	19.53
2000	17.56	4.94	22.49	17.30	2.44	19.74
2010	16.78	5.73	22.51	16.55	2.84	19.39
2020	15.99	6.28	22.28	15.80	3.12	18.92
2030	15.27	6.67	21.94	15.10	3.32	18.42

Sources: 1960-80, adapted and adjusted from Díaz (2000); 1990-2030, adapted from Serrano *et al.* (2014). Projected values.

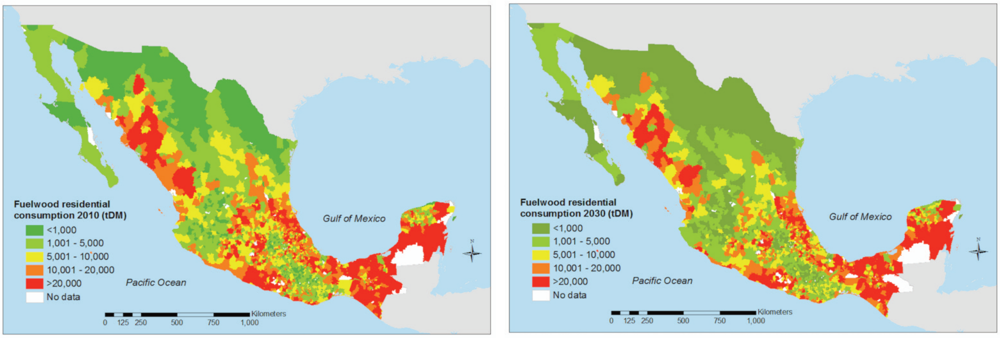
4.1.3. Spatial distribution of FW consumption

The spatial distribution of FW consumption is very heterogeneous. FW consumption is very important in the Central, Southern and Northwestern regions of the country (Figure 4, left). This spatial pattern of FW consumption is projected to prevail to the year 2030 (Figure 4, right). Change in FW consumption is also heterogeneous, while in many counties FW demand is expected to decrease, FW demand is expected to increase in se-

5. Fuelwood consumption for the 1960-80 period is also shown in Table 1.

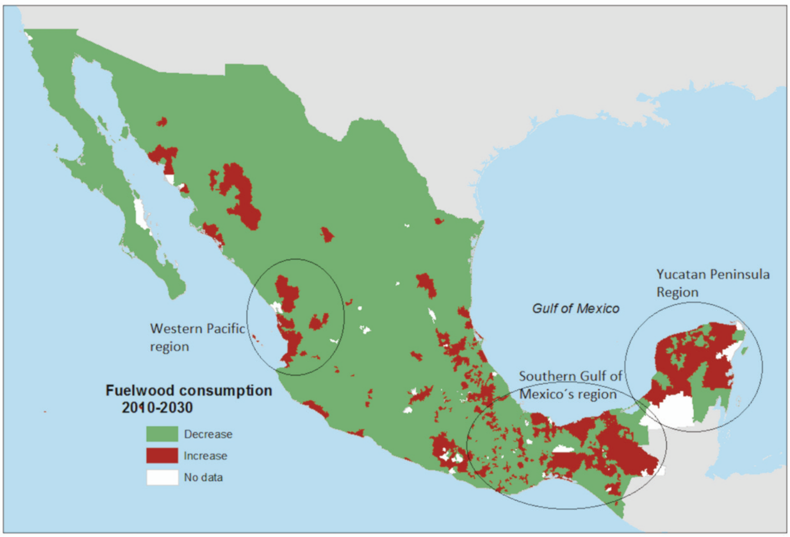
veral counties located in the Northwestern and Southeastern regions of the country (Figure 5).

FIGURE 4
Spatial distribution of FW consumption, 2010 and 2030



Source: Serrano *et al.* (2014).

FIGURE 5
FW consumption trends, 2010-2030



Source: elaborated with data using the model described in Serrano *et al.* (2014).

4.1.4. Environmental impacts of FW use

The harvesting patterns of FW and their associated impacts are also very heterogeneous in Mexico. Conventional wisdom states that all the "traditional FW harvested" contributes to forest degradation and deforestation. To test this assumption, we used a spatial-explicit model (WISDOM; Ghilardi, Guerrero & Masera, 2007) to determine the fraction of non-renewable FW (fNRB) for each of the 2,500 Mexican counties (municipality) scale (*i.e.*, the fraction of FW used that exceeds the county woody biomass growth rates). We first obtained maps of land-use provided by the National Bureau of Statistics (INEGI) and use them to estimate the productivity (supply) of the sustainable standing woody biomass that could be obtained in each county. In other words, we only accounted for the standing woody biomass that could potentially be used for FW consumption depending on the different land cover types. Estimates of sustainable FW supply were then compared to the estimated data on FW consumption per county. The fNRB in each county was obtained from the respectively balance between the sustainable supply and demand of FW. We obtained a national fNRB figure of 34%, meaning that 64% of total FW use is in fact renewable[6]. fNRB values vary a lot by county; we identified 10% of total counties that could be considered critical or "hot-spots" because they show high fNRB values. Actions to improve the sustainability of FW could be concentrated in these areas, making policy interventions more cost-effective.

Other impacts from traditional FW use include GHG emissions. From them, net CO2 emissions from FW combustion are considered to be zero when FW is extracted on a sustainable manner. Yet, other greenhouse gases (GHG's) such as CH4 and N2O and short-lived pollutants such as black carbon are released as a result of incomplete combustion of FW in open fires contributing directly to climate change. When FW is not harvested in a sustainable way, net emissions of CO2 are obtained, and they are added to other GHG's emissions like CH4 and N2O within the county. Recent studies have estimated that the cumulative emissions between 2014 and the year 2030 from FW combustion – for exclusive and mixed users– could reach about 360 MtCO2e under the business as usual scenario (BAU)[7]. This figure represents about 50% of current total Mexican GHG annual emissions. This estimate accounts for methane (CH4), carbon monoxide (CO), black carbon (BC) and net emissions of CO2 resulting from a non-sustainable extraction of FW (Serrano *et al.*, 2018). The accelerated penetration of LPG in the countryside does not contribute to reduce substantially the expected future GHG emissions

6. Refer to Ghilardi, Guerrero and Masera (2007) for a detailed explanation on the methodology behind this value.

7. Three-stone fires (TSF) are supposed to still be used instead of more efficient devices.

mainly because LPG is used in combination with TSF. On the other side, an intensive dissemination of clean woodburning cookstoves (CCS) targeting initially counties with the highest fNRB values, and including mixed LPG-FW users, helps achieve a 35% reduction in cumulative emissions by 2030. The health benefits of this last intervention are also the largest as TSF are more effectively displaced from the local kitchens when CCS are incorporated than when LPG alone is adopted.

5. DISCUSSION

Since 1960, major changes in Mexico's social, demographic and macro-economic conditions have occurred: Mexico shifted from a semi-rural to an urban country; there has been a large reduction in average rural household size; and there have also been accelerated industrialization and modernization of specific sectors of the Mexican economy including commercial agriculture. Also, during this period, Mexico switched from an oil-importing to an oil-exporting country and sustained for decades large subsidies to LPG and other fossil fuels[8].

Regarding FW use, we have seen that during the period analyzed rural Mexican households have not followed the "expected" energy transition or fuel switching from woodfuels to modern fuels proposed by the conventional energy ladder model, but a multiple fuel or *fuel stacking strategy*. In fact, while declining as total country population share, since 1960 the absolute number of FW users in Mexico has remained virtually constant and is expected to continue above 20 million people in the mid-term. At the same time, there has been an increasing growth of mixed LPG-FW users *i.e.*, LPG use in combination with FW, which is also expected to cover an increasing share of total rural households. Very rarely, when adopting LPG, rural users have completely abandoned FW. As a consequence of stacking LPG stoves with traditional woodburning open fires, the so called *modernization of rural residential cooking* has not resulted in substantial savings in FW use nor in the associated GHG emissions or in tangible health benefits, *i.e.*, there have not been reductions of indoor air pollution levels.

A number of macro- and micro-economic factors may help explain these trends. At the macro-economic level, the resilience of exclusive FW users may be explained by the large number and high-dispersion of Mexican rural villages, the existence of a large number of indigenous groups with strong attachments to culinary traditions and practices. Also,

8. Since the year 2000, however the Mexican Government has sought to make domestic LPG prices similar to international prices.

Mexico's economic development has been very unequal, favoring the urban-industrial sectors and large-commercial agriculture against rural settlements and small-farmers; as a result, over 58% rural people currently live in poverty and 17% in extreme-poverty (CONEVAL, 2017). Most of these people simply don't have the economic means to access modern fuels such as LPG.

At the household level, Masera *et al.* (2015) have described the rationale behind LPG and FW stacking as having to do with the interplay between culture, the nature and extent of residential energy needs satisfied by traditional open fires and livelihood strategies. Traditional open fires satisfy more needs that only cooking. Heating, lighting, sealing roofs, smoking of meat and crops, and providing hot water for bathing, are examples of the diverse energy services open fires usually provide. Many tasks are also involved while cooking a meal. Heating, boiling, baking or frying require each very specific energy demand in terms of fuel, device, cookware and time. Under these circumstances, LPG stoves represent partial substitutes –or suboptimal alternatives– of open fires and traditional rustic stoves. Moreover, FW use remains a back-up strategy when family cash incomes are uncertain and/or acquiring clean fuels could be difficult (such as within the rainy season). Under these conditions, fuel/stove stacking is a flexible strategy that allows families to cope with their cooking and other energy needs (Masera *et al.*, 2015).

An alternative strategy has been the inclusion of clean woodburning cookstoves (CCS) into the menu of cooking options for rural households. This strategy has been tested regionally with chimney CCS adapted to the regional conditions and cooking needs (Berrueta *et al.*, 2015). As shown by a series of case studies (see for example, García Frapolli *et al.*, 2010) and by country-wide analysis and future scenarios (Serrano *et al.*, 2018), when properly implemented to assure a sustained use over the long-term, these CCS have the potential to: a) more effectively reach the poorest FW-exclusive households, currently out of the reach of modern fuels; b) more effectively displace traditional fires, either alone or particularly in combination with LPG; and c) provide significant FW savings and mitigation of GHG emissions.

We should note finally, that there are also important regional variations in the amounts, impacts and future trends of FW use. For example, there are counties where FW users will continue to grow (particularly within Central-Western and Southern Mexico), and other where exclusive users are rapidly shifting to FW-LPG users (like in many areas of Central-Northern Mexico) (Serrano *et al.*, 2018). There is also a heterogeneous pattern of FW renewability across the territory. While most FW consumed is renewable, specific counties in Central and Southern Mexico presented large values of non-renewable FW consumption (Serrano, 2016).

6. CONCLUSIONS

We have shown that during the past 60 years FW has represented a major residential fuel for Mexican rural households. Mid-term scenarios show that this trend will continue in the foreseeable future. FW use has been resilient even with an increasing penetration of LPG in the rural areas. Complete switch to modern fuels such as LPG has proven very rare due to economic, technical and cultural reasons. The so called *energy transition* to modern fuels among rural Mexican households has actually been, for an increasing percentage of the population a *fuel stacking strategy*, where the combination of LPG with FW is providing more flexible, reliable and convenient strategy. However, for another large share of the rural population, impoverished and "left behind" under recent and current rural development and agrarian strategies, even the stacking of fuels is a dream and, if no other actions are taken, will continue relying entirely on traditional open fires with negative health and environmental consequences. Even mixed FW-LPG users, as they continue relying on traditional fires for cooking, do not get the potential large health benefits brought about by access to modern fuels.

Under these conditions, clean woodburning chimney cookstoves (CCS) have risen as a relevant cost-effective option to both more effectively displace open fires and reach a larger share of rural households. Adequately designed, implemented, and disseminated, these stoves have shown that either alone or together with other clean fuels such as LPG, could reduce FW use, provide substantive mitigation and large health benefits to local people, in particular to women. In fact, CCS dissemination has been estimated to reach up to 34% of total cumulative GHG emissions when households targeted include both exclusive and mixed users and are located within regions where FW is extracted unsustainably (Serrano *et al.*, 2018). These results confirm the importance of promoting integrated strategies that include the clean and efficient use of FW while also benefiting from increasing access to clean modern fuels.

Finally, the paper also makes clear that large disparities among rural regions exist in Mexico, in terms of the total number and future expected evolution of exclusive FW users, sustainability of fuelwood use, cultural cooking and other practices associated to traditional fires, and physical and economic accessibility to LPG. Therefore, any alternative, to be successful, will need to be regionally-specific and tailored to the local socio-environmental conditions and priorities.

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