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Spatial and temporal projection of fuelwood and charcoal consumption in Mexico

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ABSTRACT

Fuelwood and charcoal are fundamental fuel sources for the residential sector in Mexico. A Business-As-Usual (BAU) projection by means of a spatially-explicit approach was developed to assess national fuelwood and charcoal consumption for the period 2010 to 2030. The model was calibrated for 1990–2000 and 2010 projections were validated against official census data for the same year. For 2010, we estimated that fuelwood and charcoal accounted for 48% of total residential energy demand. The projection of fuelwood consumption declined slightly from 19.4 Mt (dry matter) or 310 PJ in 2010 to 18.4 Mt or 294 PJ by 2030. An important future growth of mixed fuelwood–LPG users is expected pointing out that fuel stacking rather than fuel switching out of fuelwood would prevail. Charcoal consumption increased from 3.8 Mt (dried wood equivalent) or 61 PJ to 4.7 Mt or 75 PJ during the same period. A relevant outcome of the spatial assessment was the uncovering of large variations in fuelwood and charcoal use trends among spatial units (municipalities), hidden by the national aggregated trends. This opens up the opportunity to analyze regional variability to identify priority areas regarding fuelwood and charcoal use.

Introduction

Biomass energy provided about 10.2% (50.3 EJ) of the world total primary energy supply in 2008 (Chum et al., 2011). Of these 50.3 EJ, traditional use of fuelwood along with other biomass residues mainly for cooking and heating in the poorer developing countries, contributed 30.7 EJ (Chum et al., 2011). If the informal economy sectors are included, solids biofuels, particularly fuelwood and charcoal, may contribute almost 14% of total primary energy supply globally and as much as one-third in developing countries (FAO, 2011). Furthermore, some 2.7 billion people – about 40% of the world's population – depend on biomass as their main source of energy supply. If current trends continue, the number of people relying on biomass to meet part of their energy needs, will reach 2.8 billion in 2030 (IEA, 2010). Socioeconomic scenarios indicate that reliance on fuelwood to meet energy needs is expected to continue for several decades (IEA, 2010).

Globally, there is a lack of detailed statistics on fuelwood and charcoal consumption, their spatial distribution and future projections. This is due to several factors such as the fact that a) a large proportion of fuelwood is harvested and used in rural areas without entering the formal markets and statistics, and, b) the commercial production of fuelwood and charcoal in many countries is done illegally, making the acquisition of reliable statics difficult (UNECE/FAO, 2012a). Some case studies have shown an underestimation of fuelwood consumption at national levels (Drigo, 2004, 2009; Drigo et al., 2007; Ghilardi et al., 2007). Detailed knowledge of fuelwood and charcoal use-patterns is challenging due to their dispersed nature (Arnold et al., 2003). Using aggregated data usually hides the inherent variability associated to fuelwood and charcoal spatial patterns (Arnold et al., 2003, 2006; Foley, 1987; Leach and Mearns, 1988; Lele, 1993; Mahapatra and Mitchell, 1999; Masera, 1994; RWEDP, 1997, 2000). A reliable, spatially explicit biomass fuels database is therefore a fundamental component for policy-making effectiveness (UNECE/FAO, 2012b; Ghilardi et al., 2009).

In Mexico, despite sustained government efforts to encourage the use of "modern" fuels in the residential sector, for example by subsidizing LPG, fuelwood still supplied 34% of the country's residential energy use in 2009 according to official statistics (SENER, 2009) and charcoal is still important as a complementary residential fuel. In Mexico, fuelwood is mostly used for cooking in traditional devices such as open fires and such use is concentrated in rural and semi-urban areas (Díaz, 2000). Fuel stacking is also very common (Masera et al., 2000). On the contrary, charcoal consumption is mostly located in urban localities. However, little is known about the country patterns of fuelwood and charcoal use and their future trends.

Deriving spatial estimates and future trends of fuelwood use is relevant given its social, economic and environmental impacts. For instance, indoor air pollution caused by the use of open fires in Mexican villages is several times higher than the level recommended by the World Health Organization and causes severe health problems,

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Table 1
Fuelwood per capita consumption for exclusive users per macro-ecological region.

Ecological macro-region	Fuelwood consumption (tDM/cap/yr)
Tropical forest	0.73
Deciduous forest	0.91
Temperate	1.10
Semi-arid	0.55
Wetland	0.91
Others	0.55

Source: Adapted from Ghilardi et al. (2007).

particularly in women and children (Armendáriz et al., 2008; Romieu et al., 2009).

A first approach to explore the spatial patterns of fuelwood use, the Woodfuels Integrated Supply/Demand Overview Mapping (WISDOM) methodology was developed by Masera et al. (2003, 2006). WISDOM is defined as a "spatial-explicit method for highlighting and determining priority areas of intervention and supporting wood energy/bioenergy planning and policy formulation". WISDOM integrates available data on fuelwood and charcoal demand and supply into indicators that are used to identify priority areas in terms of fuelwood demand trends, and available resources. This method was conceived as a partnership between the Wood Energy program of the FAO products forest service (FOIP) and the Ecosystems Research Centre (CIECO) of the National University of Mexico (UNAM). Currently more than 23 case studies covering sub-national studies, countries and regions in Europe, Latin America, Asia and Africa have been conducted (Drigo, 2009).

The aim of this study is to assess fuelwood and charcoal consumption patterns in Mexico from 2010 to 2030 at the county (municipality) level in a BAU scenario and based on the WISDOM approach in order to: 1) obtain more realistic estimates of the current total use of fuelwood and charcoal in the country and project trends until 2030; and 2) examine regional differences, highlighting priority action areas regarding fuelwood and charcoal consumption.

Methods

Estimation of fuelwood consumption

Total fuelwood annual consumption (CT) was estimated as the product of per capita consumption (Cpc) and saturation (S) (percentage of users) times total population, considering two types of users: exclusive fuelwood users and mixed fuelwood–LPG users. The analysis was done at the county (municipality) level, with a total of approximately 2500 units of analysis. Mathematically total fuelwood consumption per county was calculated according to Eq. (1)

$$CT_k = \sum (C_{Ek} + C_{Mk}) \tag{1}$$

Where CT_k is total fuelwood consumption in tonnes of dry matter per year (tDM/year), C_{Ek} is fuelwood consumption per county attributable to exclusive users and C_{Mk} is the fuelwood consumption per county attributable to mixed fuel users.

As stated, C_E and C_M are calculated as follows:

$$C_{E_k} = Cpc_{E_k} \times S_{E_k} \times P_k \tag{2}$$

and

$$C_{M_k} = Cpc_{M_k} \times S_{M_k} \times P_k \tag{3}$$

where Cpc_{Ek} and Cpc_{Mk} are fuelwood annual consumption per capita for exclusive and mixed use per county "k" respectively; S_{Ek} and S_{Mk} are fuelwood saturation for exclusive and mixed use per county respectively and P_k is total population per county.

Estimation of fuelwood use saturation

Fuelwood saturation for exclusive users was defined as the rate between dwellings using fuelwood to cook over total dwellings per county and it was obtained based on the National Bureau of Statistics (INEGI) county census data. Data regarding population; average inhabitants per dwelling; and dwellings using one of the following fuels for cooking: fuelwood, LPG, charcoal, electricity or oil for the years 1990 and 2000 were used to obtain number of exclusive fuelwood users. Since Díaz (2000) found that between 90 and 100% of fuelwood residential use in México is for cooking, it is assumed that dwellings using fuelwood for cooking is a good estimation of families using this fuel as a residential fuel.

Fuelwood saturation for mixed users (i.e. users of both fuelwood and LPG) was estimated as a function of fuelwood saturation for exclusive users per county. Based on case studies, Ghilardi et al. (2007) estimated that mixed fuel users accounted on average for 25% of exclusive users. Hence, we assumed that in addition to exclusive users, 25% of households in the county are mixed users. For counties where fuelwood saturation for exclusive users was above or equal 75%, fuelwood saturation for mixed users was estimated subtracting exclusive fuelwood users to the total number of users in the county. For counties where fuelwood saturation of exclusive users was less than 75%, fuelwood saturation for mixed users represented an additional 25%.

Saturation for exclusive users is calculated as follows,

$$S_{E_k} = \frac{U_{E_k}}{D_k} \tag{4}$$

where S_{Ek} is the saturation of exclusive users per county, U_{Ek} is the number of exclusive fuelwood users, and D_k is the total population in the county.

Estimation of fuelwood consumption per capita

Per capita fuelwood consumption, defined as the tonnes of dry matter (tDM) of fuelwood consumed per capita per year, was obtained for different regions by means of an exhaustive literature review for Mexico (Díaz, 2000; Masera et al., 1997; Puentes, 2002; Sánchez Gonzales, 1993; Tovar, 2004). Following the approach outlined by Ghilardi et al. (2007) average per capita consumption values for exclusive fuelwood users were obtained for each of the 5 main ecological areas in Mexico (Table 1) and then adjusted by minimum annual average temperatures with values ranging between 1 (for mild cold regions) and 1.7 (for cold regions).

To estimate per capita fuelwood consumption for exclusive users per county per year a weighted average value according to the proportion of each main ecological area within each county was used. Hence, per capita fuelwood consumption for exclusive users was estimated according to Eq. (5).

$$Cpc_{E_k} = \left(\sum_{i=1}^{5} Cpv_i \times A_i \times F_T \right)_k \tag{5}$$

where Cpc_{Ek} is the weighted annual per capita consumption for exclusive users per county, Cpv_i is the annual per capita consumption per main ecological region i per county k, A_i is the proportion of the main ecological area i in a county k, and F_T is the adjustment factor per minimum temperature per county k.

Table 2
Evolution of fuelwood users and consumption 2010–2030.

Year	Exclusive users	Mixed users	Total users	Exclusive use	Mixed use	Total use
	(Million users)			(MtDM/year)		
2010	16.8	5.7	22.5	16.6	2.8	19.4
2020	16.0	6.3	22.3	15.8	3.1	18.9
2030	15.3	6.7	21.9	15.1	3.3	18.4

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Table 3
Variability in selected fuelwood use indicators by county for 2010–2030.

Year	Total saturation	Saturation exclusive users	Saturation mixed users	Fuelwood users % growth [a]	Fuelwood Cpc [b] (tDM/cap/yr)	Counties Tot_Sat >75%	Counties Tot_Sat >85%
(Min, Max)							
2010	(0.02%, 100%)	(0.01%, 99.5%)	(0.01%, 30.9%)	(−43.8%, 9.7%)	(0.64, 1.35)	43.7%	39.1%
2030	(0.0%, 100%)	(0.0%, 99.9%)	(0.0%, 39.4%)			43.6%	40.5%

[a] Values for the period 2010–2030.
[b] Values adjusted per minimum temperatures per county. Values for the period 2010–2030.

Fuelwood use per capita consumption for mixed users is assumed to be half of exclusive users (Ghilardi et al., 2009), as shown in Eq. (6).

$$Cpc_{M_k} = 0.5 \times Cpc_{Ek} \quad (6)$$

Construction of fuelwood projection to 2030. In order to project the future annual fuelwood consumption under a business as usual scenario, it was assumed that 1) per capita consumption values remain fixed (i.e. we assumed that there will be no significant

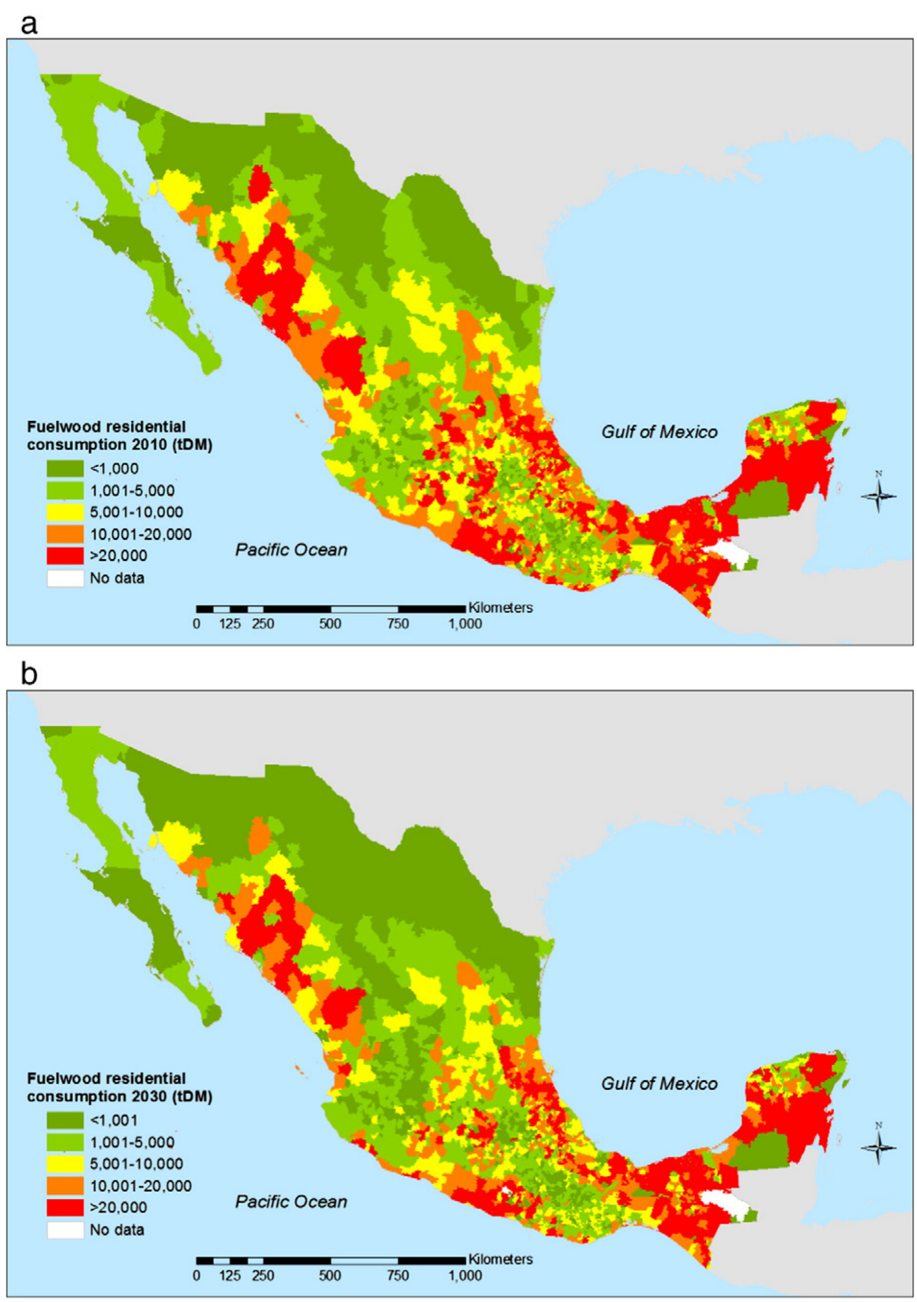

Fig. 1. Spatial distribution of residential fuelwood use. (a) For the year 2010, (b) for the year 2030.

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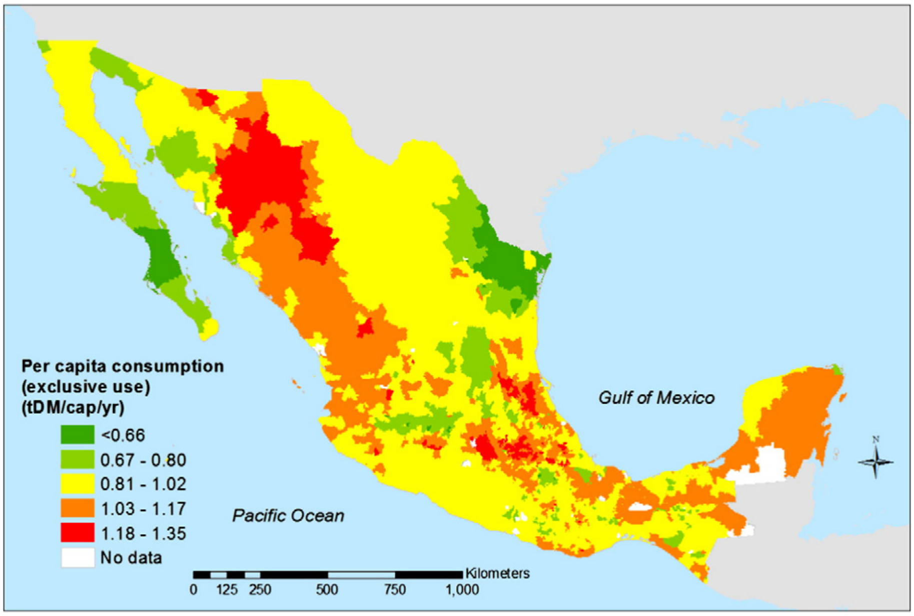

Fig. 2. Distribution of county per capita fuelwood consumption for exclusive users in Mexico 2010.

technological change in traditional devices for cooking); and 2) fuelwood saturation (for both exclusive and mixed users) change over time t, modulated by the total future population in the county k. Mathematically,

$$CT_{kt} = \left[\left(Cpc_{E_k} \times S_{E_{kt}}\right) + \left(Cpc_{M_k} \times S_{M_{kt}}\right)\right] \times P_{kt} \quad (7)$$

where CT_{kt} is the total county population at time "t"; Cpc_{Ek} and Cpc_{Mk} are per capita consumption for exclusive and mixed users, respectively; S_{Ekt} and S_{Mkt} are saturation for exclusive and mixed users at time "t", respectively; and P_{kt} is the National Population Bureau (CONAPO), projected population per county at time "t" (CONAPO, 2012).

Fuelwood saturation projection 2010–2030. The expected change in saturation for exclusive and mixed users per county "*k* "at time" *t*" was estimated assuming a logistic behavior as follows,

$$\frac{dS}{dt} = \frac{rS(K-S)}{K} \quad (8)$$

The solution to Eq. (8) is therefore,

$$S_k(t) = \frac{K \times S_{t_0} \times e^{rt}}{K + \left(S_{t_0} \times \left(e^{rt}-1\right)\right)} \quad (9)$$

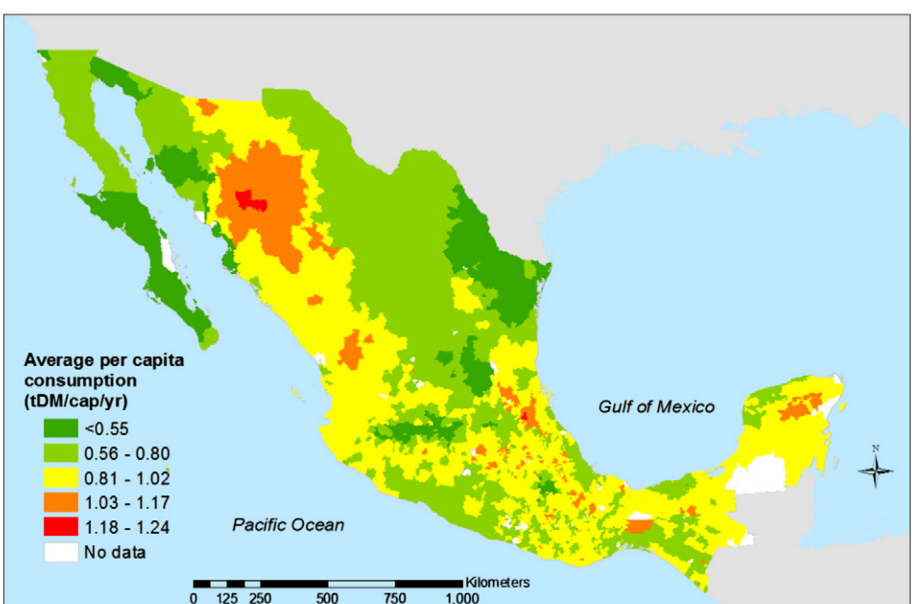

Fig. 3. Distribution of average county per capita fuelwood consumption for both exclusive and mixed users in Mexico 2010.

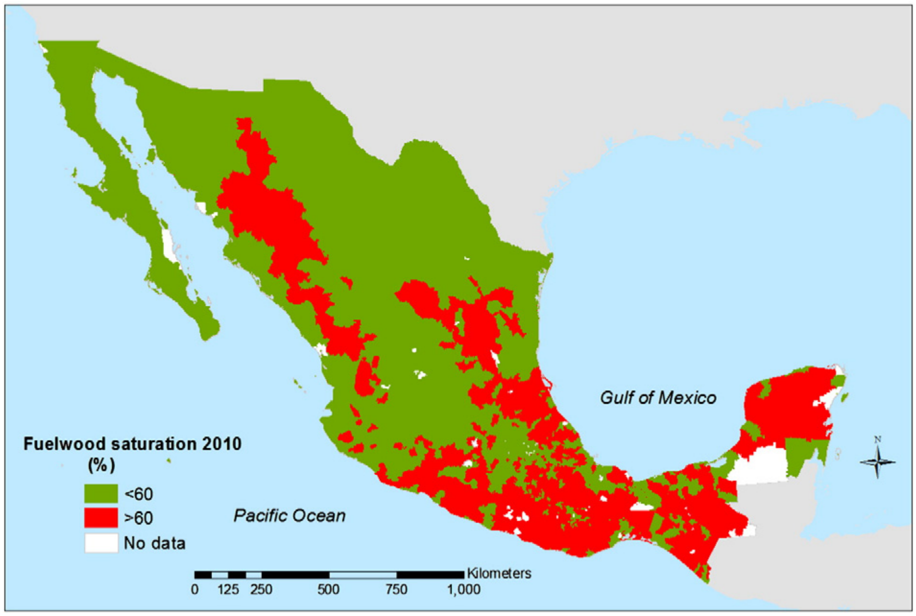

Fig. 4. Spatial distribution of counties where saturation of fuelwood users was over 60% in 2010.

Where K is the maximum saturation of fuelwood users (i.e. 1) and r, the fuelwood saturation annual growth rate for the 1990–2000 period per county "k" estimated by Eq. (10).

$$r_k = \left(\frac{S_{2000k}}{S_{1990k}}\right)^{1/t} - 1 \tag{10}$$

Saturation of users between 1990 and 2000 was used as the basis for the projection as these were the only two periods for which actual data on exclusive fuelwood users per county were available for Mexico. Data regarding residential exclusive fuelwood use per county were not included in the 2010 Census.

To reflect the increasing number of mixed fuelwood users in Mexico (Masera et al., 2000), it was assumed that the saturation of mixed users in the base year increases linearly by 1% between 2010 and the year 2030 for counties where fuelwood saturation for exclusive use was below 75%.

If fuelwood saturation < 75% then,

$$S_{Mkt} = S_{E_{kt}}(1 + (0.25 + 0.01t)) \tag{11}$$

For counties where saturation reaches more than 75%, the saturation of mixed users was simply estimated as the difference between fuelwood users and total population in the county at time "t", as stated in the Estimation of fuelwood use saturation section.

Model calibration and validation. The model was calibrated for 1990–2000 and 2010 projections were validated against official data obtained from the significant sample derived from the 2010 national census (INEGI, 2010).

Charcoal

Estimation of charcoal consumption

Annual charcoal consumption, residential and commercial (restaurants), was estimated by county, based on a detailed analysis of the specific consumption per dwelling and restaurant, and saturation of charcoal consumers per locality size in the following cities: Monterrey, Ciudad Victoria, Reynosa and Gonzalez, in the North, and San Luis Potosí, Querétaro and Villahermosa, in the Center-South of Mexico. These studies were conducted between 2005 and 2006 and were used as the base to estimate charcoal users by locality size and region in the country (see Supporting information for more details regarding the location of the case-studies examined). Only localities with more than 10,000 inhabitants were included because charcoal is mainly consumed in the urban sector.

Residential charcoal consumption estimation per locality stratum

Residential charcoal consumption was estimated as follows:

$$CR_l = D_l \times CSR_l \times SR_l \tag{12}$$

Where CR_l is residential charcoal consumption, D_l, CSR_l and SR_l are the number of dwellings per locality, dwelling specific charcoal consumption, and charcoal saturation per locality of the "l" stratum, respectively.

Commercial charcoal consumption estimation per locality stratum

Commercial charcoal consumption per locality (CC_l) was estimated for both, formal and informal (street) restaurants. An average (specific) consumption per dwelling (CSC_l) was obtained and then multiplied by

Table 4
Estimation of charcoal consumption (for both residential and commercial use) 2010–2030.

Year	Residential charcoal consumption		Commercial charcoal consumption		Total charcoal consumption	
	(Mt)	(Mt-dried wood equivalent)	(Mt)	(Mt-dried wood equivalent)	(Mt)	(Mt-dried wood equivalent)
2010	0.47	2.60	0.22	1.22	0.69	3.83
2020	0.52	2.90	0.25	1.38	0.76	4.24
2030	0.57	3.16	0.27	1.50	0.84	4.66

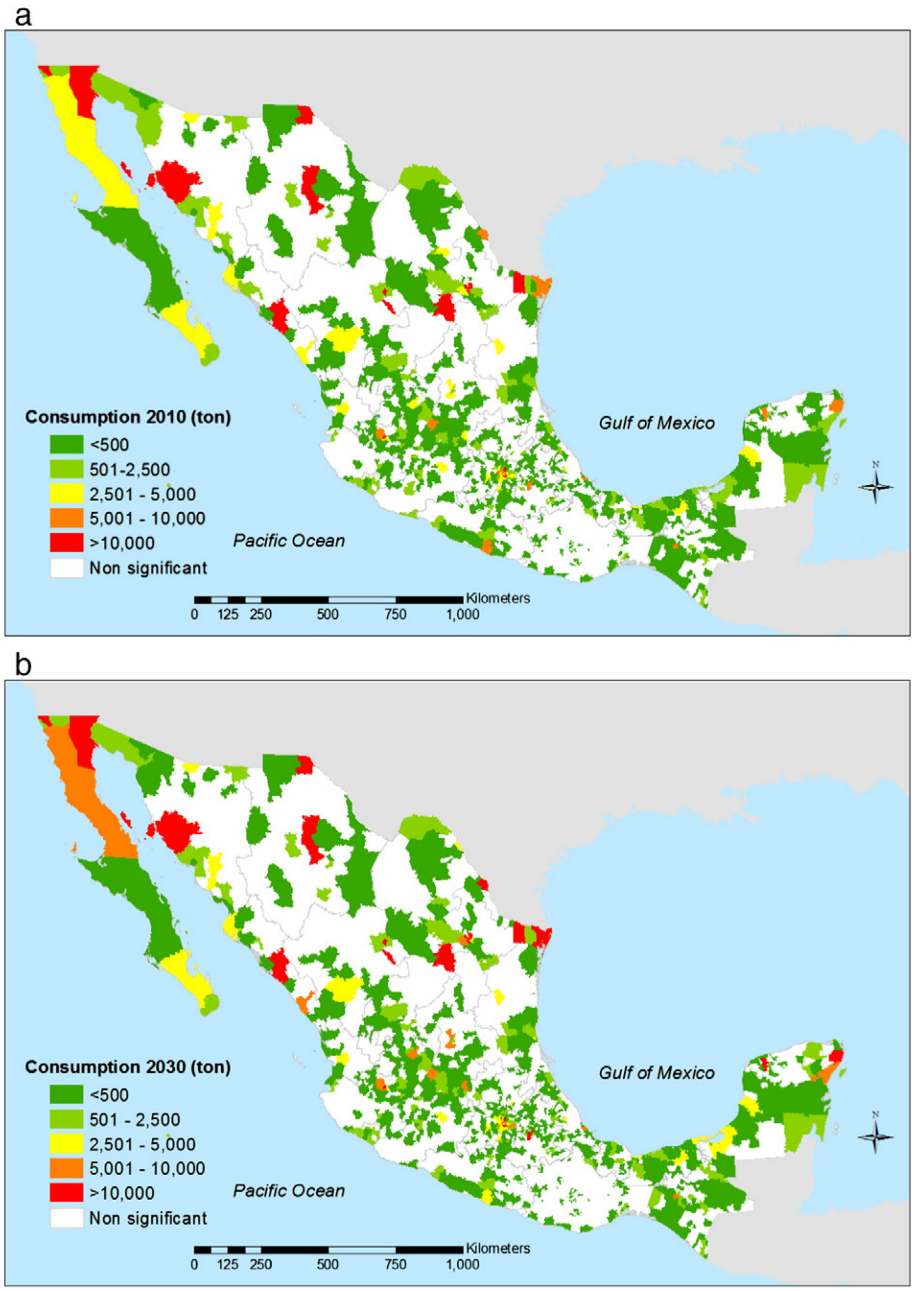

Fig. 5. Projection of charcoal consumption per county in Mexico. (a) For the year 2010, (b) for the year 2030.

the total number of dwellings in the locality, using 6 different strata as in the residential sector. Mathematically,

$$CC_l = D_l \times CSC_l \tag{13}$$

where, CC_l is commercial charcoal consumption, D_l is the total number of dwellings per locality, and CSCl is average specific consumption per dwelling.

Finally, total charcoal consumption per county "k" was estimated as the sum of residential and commercial use per locality, according to Eq. (14).

$$CT_k = \sum_{l=1}^{n} D_l((CSR_l \times SR_l) + CSC_l) \tag{14}$$

Charcoal projection to 2030

The use of charcoal was projected to 2030 assuming that the specific consumption per dwelling and the saturation of charcoal users per locality will remain fixed, and then multiplied by the official population projection (CONAPO, 2012) per locality.

Results and discussion

Fuelwood

Table 2 shows the expected evolution of fuelwood users and consumption for both exclusive and mixed users in the period 2010–2030. The number of exclusive users and their associated consumption is expected to decrease by about 9% between 2010 and 2030. In contrast, mixed users' number and their associated fuelwood use are expected to increase by 15% during the same period. Total projected fuelwood users and consumption are expected to reach levels of nearly 22 million people and 18.4 million tonnes, respectively, for 2030. Fuelwood consumption in 2010 is equivalent to 32.3 million m^3, representing almost five times the volume of commercial timber for non-energy uses

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(CONAFOR, 2012), and 41% of total residential energy demand in 2010 (SENER, 2009).

Fuelwood use showed a heterogeneous spatial pattern responding to large differences in expected trends in saturation, growth of fuelwood users and per capita consumption between counties (Table 3 and Fig. 1). With the exception of Northeastern Mexico the rest of the country is highly dependent on fuelwood (Fig. 1). The specific change in consumption per county – i.e., decrease or increase – depends on the combined effect of their 1990–2000 trends on fuel use, the expected future population demographics, and on the expected future share of mixed fuelwood users.

Fig. 2 shows the regional variability of per capita fuelwood consumption for exclusive users. As expected, higher values are found in the municipalities with colder and more forested areas of Mexico, with a range from 0.66 to 1.35 tDM/cap/yr. Fig. 3 shows the average per capita fuelwood use per county – now including both exclusive and mixed users – for the year 2010. Consumption ranges between 0.55 tDM/cap/yr and 1.24 tDM/cap/yr, depending on the municipality. The map still shows that higher per capita use is concentrated in those counties with colder and humid or semi-humid conditions, for example in the Tarahumara Region of Northern Mexico, but the variability of per capita consumption is modulated by the extent of mixed fuelwood–LPG users in each county.

A total of 1219 counties (almost half of total) had more than 60% of fuelwood users in 2010 (Fig. 4). This number decreased very slightly for 2030 (1195 counties).

The projected fuelwood use figures for 2010 were validated against its corresponding census data values and they differed only by 2.6%.

Charcoal

Table 4 shows charcoal consumption for residential and commercial use. Charcoal consumption is expected to increase almost 20% from 2010 to 2030. For 2010 total charcoal consumption accounted for about 688,000 tonnes (3.8 Mt (dried wood equivalent)) and is expected to reach about 840,000 tonnes (4.7 Mt (dried wood equivalent)) in 2030. Residential charcoal consumption is expected to continue to be the main contributor to total charcoal demand in the country during the 2010–2030 period with 70% of total use.

Fig. 5 depicts charcoal consumption for counties with localities of more than 10,000 inhabitants in the country for 2010 and 2030. It can be seen that counties in the Northern part of the country are expected to have a significant growth in consumption compared with counties in the Central and Southern regions.

The combined consumption of fuelwood and charcoal would account for 23.2 MtDM (371 PJ) in 2030, with a growth in charcoal use and a slight decrease in fuelwood use. As a result of this combined use several counties in the Yucatan Peninsula, the Southern region of the Gulf of Mexico and the Northern Pacific coast, for instance, showed a growth in consumption (from 1% to 158%) while in many other regions consumption decreased (Fig. 6).

Conclusions

To check the consistency of our model, we compared our estimates for the total number of exclusive fuelwood users in Mexico in 2010 with the Mexican Population Census (in this last Census a sample was used to get estimates of the number of exclusive fuelwood users at country level, but it was not possible to obtain values for each county). Our estimates differed by only 2.6% with the 2010 census figures, which provides confidence about the model outcome for the base year. Unfortunately, there are no comparable official estimates on the use of charcoal, as government statistics report only the charcoal that is “legally” produced in Mexico and this accounts for a small amount of the total country production.

The regional and temporal breakdown of fuelwood consumption helps to better understand fuelwood use dynamics throughout the country: although aggregated projections show little change in fuelwood use and a linear increase in charcoal use between 2010 and 2030, maps uncover a heterogeneous spatial panorama. In the case of fuelwood, regardless the slight decline at national level by 2030, many counties are expected to increase (e.g. the Yucatan peninsula) or maintain current fuelwood use levels. As a result almost half of Mexican counties are expected to remain with more than 60% fuelwood users by 2030. Also, many of the counties that showed high levels of fuelwood consumption are among the poorest in Mexico. Poor families earning minimum salaries could spend up to 25% of their monthly income on fuelwood considering an average price of US$0.12 per kg (García-Frapolli et al., 2010) in local markets.

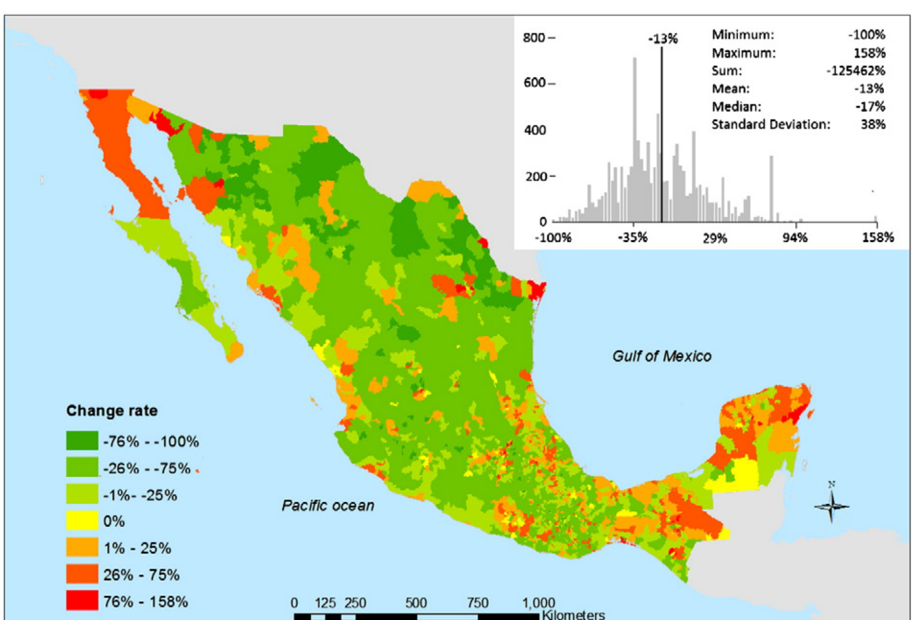

Fig. 6. Spatial variations in fuelwood and charcoal consumption trends between 2010 and 2030.

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Understanding charcoal use dynamics and its spatial patterns is also very important, as charcoal consumption was estimated to grow nearly 20% from 2010 to 2030. This significant growth has important environmental implications, because wood extraction to obtain charcoal is more intensive than fuelwood extraction for domestic use. Critical areas in terms of charcoal consumption are expected to be located in the Central and Northern regions of Mexico.

Based on the stated projections on fuelwood and charcoal demand in Mexico by 2030, alternative options to constrain negative impacts should be encouraged with particular attention to areas showing a trend of increasing biomass consumption. For example, support for projects aiming at disseminating improved woodburning cookstoves and efficient charcoal kilns would be essential to reduce demand (Berrueta et al., 2008; Masera et al., 2012), improve indoor air quality (Armendáriz et al., 2008; Masera et al., 2007), and mitigate GHG's emissions (Johnson et al., 2009, 2010).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2013.11.007.

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