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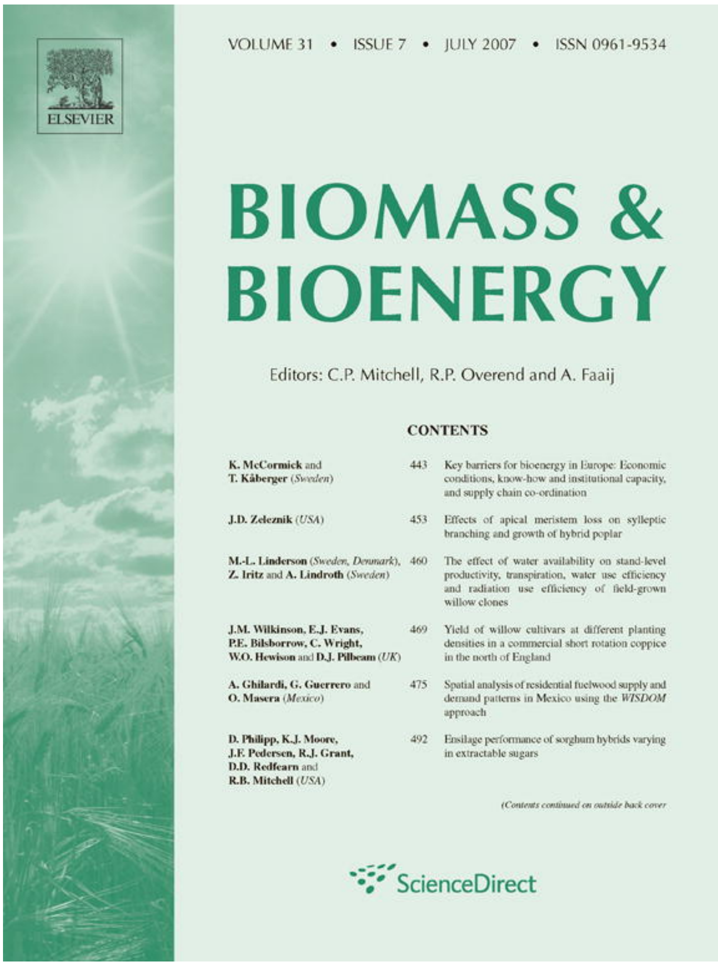

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Spatial analysis of residential fuelwood supply and demand patterns in Mexico using the *WISDOM* approach

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Abstract

A *WISDOM* analysis was conducted in Mexico in order to: (1) identify fuelwood (FW) *hot spots* in terms of residential FW use and availability of FW resources for the year 2000, and (2) estimate net CO_2 emissions from the non-renewable use of FW. *WISDOM* (woodfuel integrated supply/demand overview mapping) is a spatially explicit method, based on geographic information system (GIS) technology, which ranks a set of spatial units according to a group of indicators, in order to identify woodfuel priority areas or woodfuel *hot spots*. A comprehensive analysis was conducted, integrating full coverage national data on land cover classes, land cover change maps (1993–2000), geo-referenced population censuses (1990 and 2000), and a meticulous review of the international literature and Mexican case studies. Following a spatial multi-criteria analysis, 2395 counties (out of a country total of 2424 in year 2000) were ranked based on the number, density and annual growth rate of FW users; the percentage of households that use FW; the resilience of FW consumption, and the magnitude and likely trends of FW forest resources. The *WISDOM* analysis allowed the identification of 304 high priority counties (HPC), which showed a spatially aggregated pattern into 16 clusters. HPC cover 4% of Mexican territory and represent 27% of total FW consumption. We estimated that $1.3\,\mathrm{Tg\,CO_2\,y^{-1}}$ are released to the atmosphere by non-renewable FW burning, a value that represents less than 1% of Mexican total annual CO_2 emissions in 2002. The results of the analysis show that *WISDOM* is a useful tool for both focusing resources to critical areas where action is more needed and to obtain more accurate estimates of the impacts associated to FW use.

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Keywords: Fuelwood supply/demand; Fuelwood priority areas; Spatial patterns analysis; CO_2 emissions; Mexico

1. Introduction

In developing countries, 80% of the wood removed is used for cooking, heating, and boiling water by approximately 2.4 billion people [1,2]. On average, woodfuels satisfy 15% of developing countries primary energy consumption [1]. Although the indubitable role of woodfuels as a major energy source in these countries, its patterns of supply and demand, and its associated social, economic and environmental impacts are poorly understood [3].

The precise magnitude and likely trends of these impacts has been a controversial issue since almost three decades ago, when FW became a major item on the developing countries energy agenda. In the 1970s, the *gap* approach [4–7] predicted a severe woodfuel crisis by the year 2000. Massive deforestation and acute woodfuel scarcity situations for some 2.4 billion people were expected as a consequence of the crisis. By the mid-1980s, based on revised assessments and new field data, it was argued that the nature and impacts of the woodfuel crisis had been significantly overestimated, and that there was less of a problem than had been foreseen: woodfuel use seldom posed a serious threat of deforestation and reduced access to woodfuels was fairly easily managed by households through a number of supply and demand substitution possibilities [8,9]. The research conducted during the 1990s,

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including comprehensive field studies and projects, have shown that woodfuels demand and supply patterns are rather complex and very site specific [8–16]. Deficit situations that severely affect woodfuel users and/or negatively impact natural forests vary from place to place [8,9,14,16]. Even in regions with an overall negative woodfuel demand/supply balance, not all the places face woodfuel scarcity, and similarly, regions with an overall positive balance may include deficit areas [8,9,14,16–18].

Interest on potential FW deficits has grown recently due to their contribution to global GHG emissions. Diverse sources [19–21] indicate that the unsustainable harvest and burning of biofuels by the residential sector may account for about 4% of global CO_2 emissions. As with the *gap* approach, these estimates come however from aggregated estimates that do not incorporate the heterogeneity of local situations.

In the need for approaches that help identifying critical areas and focusing resources and/or actions on those places that actually face more acute problems, Masera et al. [3,22] developed the woodfuel integrated supply/demand overview mapping (*WISDOM*). *WISDOM* is a spatial-explicit planning tool for highlighting and determining woodfuel priority areas or woodfuel *hot spots*. To identify these critical areas or *hot spots*, spatial units of analysis at any one scale, are ranked into priority categories, by analyzing relevant interactions over a set of socioeconomic and environmental criteria and indicators, directly or indirectly related to woodfuels supply and demand patterns. Woodfuel *hot spots* can be thus established according to a number of criteria and indicators set by the users. Following a hierarchical analysis through multiple spatial scales, critical areas identified in the first step, can be further analyzed based on more accurate data. In this manner, resources can be used more efficiently and policies can be more effectively directed and tailored to the specific characteristics of the sites. *WISDOM*'s final objective is to assess the sustainable potential use of woodfuels as a renewable and widespread energy source, while supporting strategic planning and policy formulation.

So far, *WISDOM* has been conducted in Slovenia [23], Senegal [24], East Africa [25] and Southeast Asia [26]. Conducting a *WISDOM* analysis involves five main steps (Fig. 1): (1) determining the minimum spatial unit (MSU) of analysis; (2) development of the supply module; (3) development of the demand module; (4) development of the integration module; and (5) selection of the priority areas or woodfuel *hot spots*. For a complete description of the methodology and for more details about its practical implementation, existing databases, and other relevant information please refer to [3,22].

Two main objectives were defined for the Mexico *WISDOM* analysis: (1) Identify at a national scale, FW *hot spots* in terms of residential FW use and availability of FW resources for the year 2000, and (2) estimate net CO_2 emissions from the non-renewable use of FW by the residential sector for the same year. As mentioned above, *hot spots* can be defined according to a number of different criteria and indicators, depending on the objectives of the assessment. In this article, *hot spots* were defined as areas where: (a) insufficient FW resources could be negatively affecting a major number of residential FW users and (b)

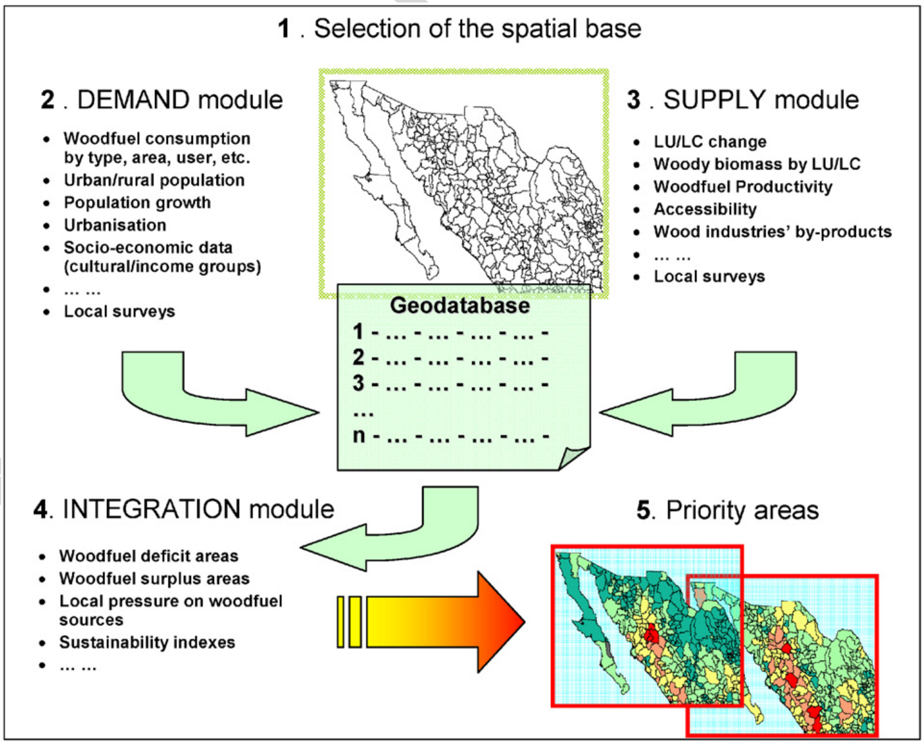

Fig. 1. *WISDOM* steps.

FW extraction for residential use could be exerting pressure on natural woody areas. Following *hot spots* definition, a relevant set of indicators associated to FW supply and demand patterns was selected.

2. Fuelwood supply and demand patterns in Mexico

In Mexico, approximately one fourth of the population cooks with fuelwood (FW), either alone or in combination with LPG [17,27]. The residential FW demand for the year 2000 was 320 PJ [28], equivalent to 32 million m^3 of wood, a volume three times higher to the total commercial timber legally harvested in the country per year [29]. FW consumption accounts for half of total residential energy demand in Mexico. Therefore, assessing the country's sustainable wood energy potential and viable options for the use of woodfuels deserve urgent attention. FW use in Mexico responds mostly to the so called ‘‘traditional pattern’’, characterized by: (a) its spatial heterogeneity, (b) being focused on the rural and household sector, (c) the widespread use of traditional technologies such as open fires, and (d) a very diverse array of extraction practices. FW in Mexico is mostly collected or bought from local markets. Although diverse sources of FW exist, it is estimated that most of it comes from forest commercial and non-commercial areas, abandoned farming plots under re-growth, and arid regions with shrub cover [30,31]. Preferred species for FW are not necessary the same as those of commercial value [28,31,32]. This represents a key problem when trying to assess the potential production of biomass as the majority of research on this area has concentrated on establishing the amounts of usable timber produced by commercial tree species (i.e. annual increment of stems) [33].

3. Methods: conducting a *WISDOM* analysis in Mexico

3.1. Data acquisition and integration into a geo-database

The data sources used for this analysis were: (a) the latest Mexican National Forest Inventory (MNFI) published in the year 2000 (1:250,000) [34], with 69 land cover classes (when considering agriculture sub-divisions, this number rises to 74); (b) the National Population Censuses for the years 1990 and 2000, in which data about number and distribution of FW users is available [27,35]; (c) a geo-referenced map of Mexican counties [36]; (d) a national land cover change map (1993–2000), obtained from crossing the MNFI, with a 1993 land use, land cover and vegetation map from INEGI (Series II), also in 1:250.000; and (e) a meticulous review of the literature [26,37–53], and Mexican case studies [28,30–32,54–58] in order to estimate FW productivities by land cover class and per capita FW consumption by macro ecological zone.

Relevant spatial and statistical information from data sources were combined into an ‘‘attribute table’’ linked to a GIS platform (i.e. geo-database). The development of a geo-database is a key tool to relate woody biomass supplies to population distribution [59–61].

3.2. Determining the minimum spatial unit (MSU) of analysis

Environmental, social and economic parameters with full nation-wide coverage are mostly available at the state or municipal sub-national administrative level of territorial division. The sub-national administrative base map determines the spatial resolution of the demand and supply modules and, consequently, the *WISDOM* level of analysis and priority zoning. For the Mexican *WISDOM* analysis, the MSU selected was the county or ‘‘municipio’’, which is the second sub-national administrative level of territorial division. Disaggregated census data by county is available for Mexico at the Mexican National Bureau of Statistics (INEGI) web page [62]. The Mexican geo-referenced county map was published in 1995 and is available from INEGI for the 2424 counties existing in 1995, excluding insular territory. Due to geo-statistical changes at the bureaucratic level (counties are merged, divided, created and deleted frequently [63]), only those counties that could be tracked all the way during the ten year period (1990–2000) were incorporated into this analysis (2395 counties).

3.3. Supply module

3.3.1. Assumptions

The fuelwood supply capacity (FSC) of an area is a function of: (a) FW stocking and productivity of land cover classes (natural formations and anthropic landscapes); (b) land cover relative changes; and (c) accessibility [3,61,64]. Assumptions for these variables were set in order to calculate indicators values. Although wood residues from commercial logging, sawmills and construction activities may represent an important source of FW in specific areas, they were not considered in the analysis as census data on these activities is only available at the country level.

3.3.1.1. Fuelwood productivity by land cover class. The FW productivity of an area is a function of the aboveground woody biomass productivity of trees, shrub and herbaceous species by land cover class, including the rate of coarse dead wood accumulation, less the fraction of wood with alternative potential uses (e.g. commercial logging of stems with DBH >30 cm [7,64]. Within the scope of identifying priority areas where the supply/demand balance indicates a possible deficit, the supply module may use indicative biomass productivity indices based on ecological characteristics [3].

FW productivities of different land cover classes were assigned using the latest MNFI [34] plus a meticulous review of the literature [26,37–53]. The MNFI was conducted over a period of a year and was based upon

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data from INEGI and Landsat ETM-7 imagery. The procedure followed the interdependent interpretation method [65], which chiefly includes visual up-dating of the classes modified between the reference data base (Series II) and the current image (Landsat ETM-7 from 2000). The legend is hierarchical with four levels, namely, vegetation formations, vegetation types, vegetation communities and vegetation sub-communities, giving a total of 74 classes (69 when merging agricultural land covers). The inventory was subjected to a reliability assessment with the aid of digital aerial photography (scale 1:15,000) [66]. For the purpose of the present work, an aggregated legend was derived from de MNFI. Table 1 summarizes the information gathered through the literature review and shows FW productivity assumptions for each aggregated land cover class (13 classes) in the supply module.

Table 1
Aggregated land cover classes linked to fuelwood productivity estimates

Land cover class	FW increment in ($Mg\,ha^{-1}\,y^{-1}$)[a]	Range[b]	References
Tropical evergreen primary forest	3.1	1.1–5.1	[37]
Tropical evergreen secondary forest	2.8	0.7–4.9	[38]
Tropical deciduous primary forest	1.5	1.2–1.8	[39]
Tropical deciduous secondary forest	1.2	0.6–1.8	[39]
Primary coniferous forest	2.1	0.6–3.6	[40–45]
Primary coniferous and broadleaved forest	2.4	0.7–4.1	[40–45]
Primary broadleaved forest	2.6	0.8–4.4	[40–45]
Secondary coniferous forest	1.7	0.5–2.9	[40–45]
Secondary coniferous and broadleaved forest	2.0	0.6–3.4	[40–45]
Secondary broadleaved forest	2.3	0.7–3.9	[40–45]
Primary scrubland	1.6	1.0–2.2	[46–48]
Secondary scrubland	1.3	0.7–2.0	[46–48]
Mangroves	5.1	3.4–6.8	[49–52]
Agriculture/pasture[c]	0.8	0.0–1.5	[26,53]

Notes: In spite of the fact that most authors agree on the important role of non-forest sources in supplying FW for households, the studies providing objective measurement are extremely rare [26]. The value assumed for this land cover class should be regarded as a first approximation.
[a]Aboveground woody biomass suitable as FW in dry weight.
[b]Based on minimum and maximum values reported in the literature.
[c]Non-forest sources of woody biomass (anthropic landscapes): agriculture and pasture lands.

3.3.1.2. Fuelwood production changes between years 1993 and 2000. Land cover changes associated with deforestation, negatively affect FW supply in the medium and long term. The annual rate of change of FW production by county, between years 1993 and 2000, was estimated. A simplified legend was derived from de MNFI, with six land cover classes. A matrix resuming increments and decrement in FW productivities due to land cover changes that occurred between years 1993 and 2000 was constructed (Table 2). Values in Table 2 were then multiplied by the area that undergo each land cover transition between years 1993 and 2000, in order to obtain positive and negative variations in FW production by county due to land cover changes.

3.3.1.3. Accessibility. Fuelwood, either for household self-consumption or for commercialization in local markets, comes mostly from areas within limited distances from localities [30–32,58,64]. The main scope of accessibility analyses is to relate woody biomass supply to population distribution [59,64]. Distance to FW sources is a variable commonly reported in the literature. Based on a review of case studies for Mexico [30–32,58], buffers around main roads and localities were set to define

Table 2
Variation in fuelwood increments due to land cover changes

1993	2000					
	Agriculture/pasture	Other[a]	Primary temperate and tropical forests	Secondary temperate and tropical forests	Primary scrublands	Secondary scrublands
Agriculture/pasture	0.0	−0.3	1.5	1.2	0.8	0.5
Other[a]	0.3	0.0	1.8	1.6	1.2	0.9
Primary temperate and tropical forests	−1.5	−1.8	0.0	−0.2	−0.6	−0.9
Secondary temperate and tropical forests	−1.2	−1.6	0.2	0.0	−0.4	−0.7
Primary scrublands	−0.8	−1.2	0.6	0.4	0.0	−0.3
Secondary scrublands	−0.5	−0.9	0.9	0.7	0.3	1.0

Notes: Variations in FW increments were obtained as the difference between average increments by land cover class: (e.g. from primary scrubland in 1993 ($1.6\,Mg\,ha^{-1}\,y^{-1}$) to secondary scrubland in 2000 ($1.3\,Mg\,ha^{-1}\,y^{-1}$), = ($-0.3\,Mg\,ha^{-1}\,y^{-1}$)). Average increments by land cover class were obtained from Table 1, by weighting FW increments assumptions with accessible land cover areas: (1) agriculture/pasture = $0.8\,Mg\,ha^{-1}\,y^{-1}$; (2) other = $0.4\,Mg\,ha^{-1}\,y^{-1}$; (3) primary temperate and tropical forests = $2.2\,Mg\,ha^{-1}\,y^{-1}$; (4) secondary temperate and tropical forests = $2.0\,Mg\,ha^{-1}\,y^{-1}$; (5) primary scrublands = $1.6\,Mg\,ha^{-1}\,y^{-1}$; and (6) secondary scrublands = $1.3\,Mg\,ha^{-1}\,y^{-1}$.
[a]Urban areas, lakes, mangroves, and areas with no woody vegetation or no vegetation at all.

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accessible areas at the national scale. Only those localities with at least 20 houses that use FW as the only fuel source were considered (41,014 localities in year 2000, where 91% of total FW users live [27]). Accessible areas (i.e. accessible buffers) were calculated considering circles of 10 km radius around localities and 3 km at each side of main roads. Accessible areas cover almost 70% of total Mexican territory.

3.3.2. Indicators used in the supply module

Two poorly correlated indicators (Pearson correlation) related to FW supply were incorporated into the thematic attribute table of the supply module. Indicators' values, disaggregated by county, were calculated through the spatial integration of basic data using ArcView (version 8.2). The indicators are

$$S = \sum_{j=1}^{13} (A_j * P_j), \tag{1}$$

where S is the FW supply per county in $\mathrm{Mg\,y^{-1}}$ (dry matter); A_j is the county accessible area by land cover "j" in ha and P_j is the FW productivity by land cover "j" in $\mathrm{Mg\,ha^{-1}\,y^{-1}}$.

$$L_C = \sum_{k=1}^{6} (A_k * \Delta P_k)/7, \tag{2}$$

where L_C is the annual variation in aboveground woody biomass production per county in $\mathrm{Mg\,y^{-1}}$, due to land cover changes that occurred between years 1993 and 2000 in Mexico; A_k is the county accessible area by land cover transition "k" in ha (e.g. from primary scrubland to secondary scrubland); and ΔP_k is the FW productivity change (positive or negative) by land cover transition "k" in $\mathrm{Mg\,ha^{-1}\,y^{-1}}$ (Table 2).

3.4. Demand module

3.4.1. Assumptions

Significant variations in per capita FW consumption have been reported in the literature according to areas with varying supply of woody resources (i.e. eco-regions) [67–69]. We assumed average per capita FW consumption by major ecological zone (temperate, tropical, dry, wetlands and other) based on a comprehensive review of case studies and surveys in Mexico [28,30–32,54–58] (Table 3).

3.4.2. Indicators used in the demand module

Six poorly correlated indicators (Pearson correlation) related to FW demand, were incorporated into the thematic attribute table of the demand module. These indicators are

$$T = U + M, \tag{3}$$

where T represents total users per county; U are exclusive FW users per county and M represents mixed users per county (people that use both FW and LPG). U is a variable reported by INEGI while M is estimated adjusting U through a coefficient (0.25) based from Diaz [28]. The accuracy of the coefficient was tested using local surveys, where exclusive and mixed users are reported [28], vs. INEGI census data by locality, were only exclusive users are reported [27].

Table 3
Average per capita fuelwood consumption in Mexico

Major ecological zone	Per capita FW consumption in ($\mathrm{kg\,day^{-1}\,cap^{-1}}$)	Range[a]
Tropical humid	2.0	1.5–2.5
Tropical dry	2.5	1.9–3.1
Temperate	3.0	2.2–3.7
Semi-arid	1.5	1.1–1.9
Wetlands	2.5	1.9–3.1
Other	1.5	1.1–1.9

Notes: Own estimates based on a review of existing studies. Consumption values are in dry weight. cap = per capita.
See also Diaz [28] for a comprehensive review of case studies and surveys in Mexico.
[a]Based on minimum and maximum values reported in the literature for Mexico.

$$D = (U + M * 0.5)/A, \tag{4}$$

where D is the FW users' density per county in users' $\mathrm{ha^{-1}}$; A is the county accessible area in ha. Mixed users were multiplied by 0.5 as per capita FW consumption is half of that assumed for exclusive users. Only FW users within accessible areas were considered (see Section 3.3.1.3).

$$\mathrm{SAT} = F/H, \tag{5}$$

where SAT is the saturation per county, F are the number of households that use FW per county, and H are the total number of households per county.

$$\lambda = (U_t/U_o)^{1/t}, \tag{6}$$

where λ is the discrete rate of FW users' growth between years 1990 and 2000 per county; U_t are FW users per county in year 2000; U_o are FW users per county in year 1990 and t is 10 years.

$$I = I_N/P_T, \tag{7}$$

where I is the percentage of people belonging to an ethnic group per county; I_N is the number of people over 5 years old that speaks an indigenous language per county and P_T is total population per county. This variable is linked to FW use patterns as a proxy measure of the resilience of consumption, as FW use is a cultural characteristic of most ethnic groups in Mexico.

$$C = \sum_{i=1}^{5} (\mathrm{CU}_i * f_i * \mathrm{Cl}) * (U + M * 0.5), \tag{8}$$

where C is the FW consumption per county in $\mathrm{Mg\,y^{-1}}$ (dry matter); CU_i is the per capita FW consumption per

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county by major ecological zone "i" in $\mathrm{Mg\,y^{-1}}$ (dry matter); f_i is the percentage of total county area covered by major ecological zone "i"; and Cl is a coefficient that adjusts per capita FW consumption by minimum average annual temperatures per county (ranging from 1 in mild cold regions to 1.7 in cold areas). Mixed users were multiplied by 0.5 as per capita FW consumption is half of that assumed for exclusive users.

3.5. Integration module

The information gathered in the supply and demand modules was combined to estimate a FW supply-demand balance (B), disaggregated by county, that was used to complete the integration module.

$$B = S - C, \tag{9}$$

where B is the balance between FW supply and demand per county in $\mathrm{Mg\,y^{-1}}$ (dry matter). Consumption (C) in this equation was adjusted for those FW users within accessible areas (see Section 3.3.1.3).

3.6. Identification of Mexican fuelwood hot spots

In order to identify Mexican FW *hotspots*, the methodological approach described by Geneletti [70] was followed. This approach uses a geographical information system (GIS) and a spatially explicit Multi-criteria analysis (MCA) to identify priorities among spatial units, represented by Mexican counties in this article. Counties are assessed by means of selected FW supply and demand indicators, and then ranked by using MCA techniques. Four steps were followed: (1) standardization of indicators, (2) weight assignment, (3) aggregation procedure, and (4) construction of a fuelwood priority index (FPI).

3.6.1. Standardization of indicators

Indicators in the supply, demand and integration modules were standardized by generating a linear value function (i.e. a function that expresses the relation between the variable or indicator real value and the corresponding value score (between 0 and 1) [70,71]. Maximum and minimum thresholds were set to eliminate extreme real values from the value function. Indicator's extreme maximum and minimum values were set to 1 and 0, respectively. See Appendix.

3.6.2. Weight assignment and aggregation procedure

Following Geneletti [70], three different weight sets were assigned to indicators in order to include different perspectives into the priorization analysis (Table 4). In the first set, equal weights were assigned to all indicators (70% of the overall weight distributed within five demand indicators and 30% within two supply/integration indicators). In the second set, 90% of the overall weight was distributed between FW supply/integration indicators, such as balance and land cover change, while in the third set, 90% of the overall weight was distributed between demand indicators. From the aggregation techniques available in environmental MCA [72], and given the high number of spatial units to be compared and the quantitative nature of indicators, the weighted summation technique is the most appropriate for this study, and consists in adding all weighted standardized scores from all indicators used.

The weighted summation output (WSO) per county by weight set "s" is given by the equation:

$$\mathrm{WSO_s} = \sum_{d=1}^{7} R_d * W_{ds}, \tag{10}$$

where R is the standardized score per county for each indicator "d"; and W is the weight assigned for each indicator "d" and weight set "s". As standardized scores are used, values of WSO vary between 0 and 1.

3.6.3. Construction of a FPI

The final step in the priorization analysis was to select the top-scoring counties within the three weighted summation

Table 4
Indicators and weights used in the priorization analysis

Indicator	Abbrev.	Equation	Unit	Module of origin	Weight Set 1	Weight Set 2	Weight Set 3
FW users	T	(3)	number of users	Demand	0.14	0.02	0.20
FW density	D	(4)	number of users $\mathrm{ha^{-1}}$	Demand	0.14	0.02	0.20
Saturation (households)	SAT	(5)	%	Demand	0.14	0.02	0.20
FW users' growth (1990–2000)	λ	(6)	%	Demand	0.14	0.02	0.20
Percentage of people belonging to an ethnic group	I	(7)	%	Demand	0.14	0.01	0.10
FW balance	B	(9)	$\mathrm{Mg\,y^{-1}}$	Integration	0.14	0.50	0.05
Land cover change (1993–2000)	L_C	(2)	$\mathrm{Mg\,y^{-1}}$	Supply	0.14	0.40	0.04
				Total	1.00	1.00	1.00

Notes: Totals do not match because of round up. Note that FW supply (S) and consumption (C) indicators were replaced by FW balance (B).

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Table 5
WSO thresholds and number of counties in each category

FPI group	WSO threshold value
High priority	>0.5
Mid-high priority	0.4–0.5
Mid-priority	0.3–0.4
Mid-low priority	0.15–0.3
Low priority	<0.15

Notes: Mid-high priority counties include counties in which each value of the three WSO is higher than 0.4 and at least one value is between 0.5 and 0.4; mid priority counties are those in which each value of the three WSO is higher than 0.3 and at least one value is between 0.4 and 0.3; mid-low priority counties are those in which each value of the three WSO is higher than 0.15 and at least one value is between 0.3 and 0.15. The FPI priorization rationale is that counties can be ranked consistently with all the three weight sets assumptions (i.e. equal weighted, demand indicators weighted more, supply and integration indicators weighted more, see Table 4). For example, counties with low balance (B) and land cover change (L_C) values but high demand indicators values (i.e. $T, D, \mathrm{SAT}, \lambda$ and I), will not be ranked as top scoring as the WSO_2, in which B and L_C are given higher weights, will be low. If no weights were assigned and a simple summation was done, high value demand indicators could bias the overall county score.

outputs ($\mathrm{WSO_s}$). This selection was done by a FPI that ranks counties in five groups of priority according to four WSO thresholds (Table 5).

3.7. Uncertainty in basic data assumptions

Although *WISDOM* is meant to provide relative/qualitative values rather than absolute/quantitative data, incorporating uncertainties in the analysis gives a better idea of FW *hot spots* spatial ranges. The same methodological approach described above for identifying FW *hot spots* was conducted using maximum and minimum assumptions. Uncertainties in basic data were incorporated into the analysis for: (1) land cover productivity, (2) accessibility, (3) number of mixed users, and (4) per capita consumption. Table 1 shows uncertainties for each land cover class FW productivity estimate, based on reported ranges. Accessibility assumptions set in the priorization analysis were considered maximum (almost 70% of total territory) (see Section 3.3.1.3). For the minimum accessible area, those assumptions were set to 5 km radius around localities and 0.5 km at each side of roads. Minimum accessible areas cover almost 45% of Mexican total territory. Based on Diaz [28], maximum mixed users estimation was done using a coefficient of 0.50, instead of 0.25 (see Eq. (3)). Minimum FW users were set as only those users reported by INEGI (see Eq. (3)). Uncertainty in per capita FW consumption was set to 25% according to a review of reported values in the literature for Mexico [28,30–32,54–58].

Two new categorizations, based on the FPI, were developed: a permissive one using: (1) maximum FW productivities, (2) maximum accessible areas, (3) only exclusive users reported by INEGI (i.e. mixed users were not considered), and (4) minimum per capita consumption; and a restrictive one using: (1) minimum FW productivities, (2) minimum accessible areas, (3) maximum mixed users estimation based on Diaz [28] and (4) maximum per capita consumption.

3.8. Net CO_2 emissions estimation methods

Non renewable use of FW (i.e. when the amount extracted and burned exceeds the growth rate of the living biomass sources) contributes to net CO_2 emissions. On the contrary, when harvested and used sustainably, woodfuels are CO_2 neutral [21]. It should be noted that, due to the poor efficiencies of traditional biomass burning devices (e.g. three stone fires), FW burning (even renewably harvested) contributes with substantial GHG emissions through products of incomplete combustion (PIC) as CH_4, N_2O, CO, and NMHC [73]. Quantifying the emissions of these non-CO_2 gases associated to FW burning is difficult because few field studies are currently available that estimate their emission factors. Because of this problem, in this study we only estimated net CO_2 emissions.

Based on our *WISDOM* geo-database for Mexico, we quantified the net CO_2 emissions from non-renewable FW use at the national level using the following equation:

$$E = B * 0.5 * 3.67, \quad (11)$$

where E are net CO_2 emissions per county for $B<0$ and $E=0$ for $B \geqslant 0$; 0.5 is the carbon density of dry wood and 3.67 the ratio between the molecular weight of carbon dioxide (CO_2) and carbon (C).

4. Results

4.1. Averages values for Mexico

As shown in Table 6, accessible FW supply for Mexico was estimated in 182 Tg y^{-1}, with a mean value per county of 75 kt y^{-1}. On average, FW supply in Mexico is more than enough to satisfy FW demand (19 or 17 Tg y^{-1} considering only FW users within accessible areas). In terms of a national average balance, this surplus corresponds to 165 Tg y^{-1}. Fuelwood supply partially depends on counties accessible area. Maximum values of FW production per county (2.3 Tg y^{-1}) correspond to two Quintana Roo State counties in Southern Mexico, with accessible areas of about one million ha each. The maximum value of FW consumption (180 kt y^{-1}) corresponds to a county of Estado de Mexico State, located within an identified FW *hot spot* (see below). Annual FW losses because of land cover change within accessible areas were estimated in 1.8 Tg y^{-1}, and represent 1% of total FW supply per year and 10% of annual FW consumption coming from accessible areas (17 Tg y^{-1}). Fuelwood users' growth annual rate (1990–2000) in Mexico is slightly negative. In the 10 year period between national censuses,

Table 6
Descriptive statistics of indicators aggregated at the national level

Indicator	Total	Mean (by county)	Standard error	Minimum value	Maximum value
FW supply (*S*), Tg y^{-1}	182.487	0.075	0.003	0.000	2.256
Land cover change (1993–2000) (L_C), Tg y^{-1}	−1.802	−0.001	0.000	−0.035	0.012
FW users (*T*) in number of users	21,755,561	8975	258	0	162,543
FW users' density (*D*) in users ha^{-1}	–	0.36	0.01	0.00	8.47
Saturation (SAT) in percentages	–	48%	1%	0%	100%
FW users' annual growth (1990–2000) (λ) in percentages	–	−1.5%	0.1%	−16.2%	12.4%
People belonging to an ethnic group (*I*) in percentages	–	18%	1%	0%	90%
FW consumption (*C*) in Tg y^{-1}	19.278	0.008	0.000	0.000	0.180
FW balance (*B*) in Tg y^{-1}	165.003	0.068	0.003	−0.088	2.186

Notes: National FW consumption was estimated in 17.484 Tg y^{-1} when considering only those FW users living in accessible areas (i.e. localities with 20 or more houses that use fuelwood).

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exclusive FW users decreased from 28% to 22% of Mexico total population. These values are congruent with global trends in FW consumption [74]. Although the percentage of total fuelwood users in Mexico is decreasing, its absolute value, as well as FW consumption, has changed very little (from 22.5 to 21.8 million users and 19.8 to 19.3 Tg y^{-1} in 2000 and 1990, respectively), particularly because of the increase of mixed users. Table 6 shows Mexican national totals, mean values, and range of indicators.

Following De Montalembert and Clement [7], per capita FW supply in Latin America ranged between 0.1 and 1.3 m^3 cap^{-1} y^{-1} in the 1980s. Using a mean wood density of 0.6, we estimated that per capita FW supply in Mexico for year 2000 was approximately 14 m^3 cap^{-1} y^{-1} or 23 kg cap^{-1} day^{-1}. This difference is not surprising since one of the main criticisms of the *gap* approach was that it under-estimated FW supplies (e.g. not considering trees in anthropic landscapes).

Using a different approach, our estimate of FW consumption (321 PJ), is very similar to the one reported by Diaz [28] (320 PJ), while is considerably higher than the Mexican Energy Agency [75] estimation (252 PJ) for the year 2000.

4.2. Priorization analysis

Indicators' real values (prior to standardization) were spatialized into thematic maps to illustrate the diverse aspects of FW use patterns in Mexico. Table 7 summarizes, for each indicator, the distribution of counties into five categories which were set according to thresholds values. Fig. 2 shows the spatial distribution of high priority counties (HPC) for nine indicators. It is interesting to note the uneven spatial distribution of these HPC regarding different indicators. For example, different spatial distributions exist between HPC regarding FW losses due to land cover change and FW users (Fig. 2B vs. C). This result is congruent with most of the literature (reviewed in Arnold et al. [8,9]), suggesting that FW depletion is linked to land cover changes not necessary related to the extraction of wood for fuel. Fig. 3 shows the FW balance between FW supply and demand in Mexico for the year 2000, in which all five categories are shown.

Conducting a *WISDOM* analysis for Mexico allowed the categorization, in five groups of priority, of 2395 counties. Following a priority ranking approach (i.e. FPI) based on seven indicators, the *WISDOM* analysis for Mexico allowed the identification of 304 HPC, which represent 13% of the total number of counties analyzed (2395), and 4% of the Mexican territory. Fig. 4 shows the number of counties in each FPI category.

Tables 8 and 9 show the average and standard error values of indicators and selected variables of interest according to the five groups of counties defined by the FPI ranking. For most indicators, mean values for HPC differ considerably from national averages shown in Table 6. This responds to the WISDOM's priorization procedure, in which the FPI is constructed selecting those counties where indicators real values are more critical in terms of fuelwood use and resource availability. For example, average FW supplies for Mexico were estimated in 75 Gg y^{-1} per county, but when considering only those 304 HPC, this value decreases to 37 Gg y^{-1} per county. HPC represent 27% of total FW consumption (5 Tg out of a country total of 19 Tg) and 27% of FW users (6 million users out of a country total of 22 million). FW user's average annual growth regarding HPC is 1.5%, in contrast with the negative national average of −1.5%. HPC are characterized by a high ratio of rural/urban population (2.4) and a very low welfare index (2 in a scale from 1 to 7). These results corroborate that FW in Mexico is mostly used by the rural poor (note that these two variables where not included in the priorization analysis). As seen by standard error values, significant differences exist between indicators' mean values, regarding different FPI groups.

The five most critical states according to the percentage of their area covered by HPC are Yucatan (33% of its area; 37 HPC); Guerrero (18% of its area; 16 HPC); Puebla (17% of its area; 47 HPC); Chiapas (16% of its area;

Table 7
Thresholds values for the construction of thematic maps

	Indicator's real value thresholds	Number of counties	Indicator's real value thresholds	Number of counties	Indicator's real value thresholds	Number of counties
	FW supply (S) (Gg y^{-1})		Land cover change (1993–2000) (L_C) (Gg y^{-1})		FW users (T) in number of users	
High priority	<5	339	$<(-2.0)$	232	$>20,000$	286
Mid-high priority	5–20	666	(-2.0)–(-0.5)	454	20,000–10,000	388
Mid priority	20–50	617	(-0.5)–(-0.1)	583	10,000–5000	457
Mid-low priority	50–100	349	(-0.1)–0	571	5000–2,500	471
Low priority	>100	452	>0	583	<2500	822
		2423		2423		2424
	FW users' density (D) in users ha^{-1}		Saturation (SAT) in percentages		FW users' growth (1990–2000) (λ) in percentages	
High priority	>0.75	313	100–90	381	>1.5	329
Mid-high priority	0.75–0.25	704	90–70	448	1.5–0.5	317
Mid priority	0.25–0.10	581	70–50	322	0.5–0.0	158
Mid-low priority	0.10–0.05	268	50–30	343	0.0 to -2.5	826
Low priority	<0.05	557	30–0	930	<-2.5	766
		2423		2424		2396
	People belonging to an ethnic group (I) in percentages		FW consumption (C) (Gg y^{-1})		FW balance (B) (Gg y^{-1})	
High priority	90–70	256	>20	241	<0	186
Mid-high priority	70–50	156	20–10	362	0–10	648
Mid priority	50–10	360	10–5	400	10–25	483
Mid-low priority	10–1	575	5–1	971	25–50	398
Low priority	1–0	1077	<1	450	>50	708
		2424		2424		2423

Notes: Fuelwood supply (S) and demand (C) indicators were not used in the construction of the FPI as separate indicators but as FW balance (B), being C adjusted for users living in accessible areas. Total counties for λ (2396) differ from the rest of indicators (2424) because administrative inconsistencies exist between 1990 and 2000. Total counties for S, L_C, D and B (2423) differ from the rest of indicators (2424) because of an error in spatial data of one county in the state of Yucatan.

35 HPC); and Veracruz (16% of its area; 55 HPC). The number of HPC in Oaxaca rises to 72, but they represent only 8% of the state total area. On the contrary, only two HPC in Campeche account for 6% of this state total area (Table 10).

An interesting result of the FPI ranking is the aggregated spatial pattern of most HPC within larger clusters. Based on these counties number and distribution (considering both, permissive and restrictive perspectives), 16 clusters were preliminary identified (Fig. 5). Many of these clusters coincide with ethnic groups distributions, although this indicator has a minor weight in the analysis. This result is congruent with the fact that in Mexico, the rural poor population sector is often represented by people belonging to ethnic groups.

As mentioned in Section 3.7, two additional rankings of Mexican counties were conducted, following both a permissive and restrictive perspectives. Fig. 6 show the national averages standardized scores and real values of four indicators subject to uncertainties in basic assumptions, as compared with the variation in HPC following the three FPI rankings (i.e. permissive assumptions, mean assumptions and restrictive assumptions). The variation between HPC based on the FPI ($439-174=265$) represent 11% of total counties ranked (2395). This result shows that the *WISDOM* priorization methodology is robust enough for identifying relatively circumscribed areas, since maximum and minimum basic assumptions were set based on extreme values cited in the literature. For example, an uncertainty of almost 100% was set to FW productivity assigned to agriculture areas (which cover 41% of maximum accessible areas), ranging from a minimum value of 0.04 Mg ha^{-1} y^{-1}, to a maximum value of 1.47 Mg ha^{-1} y^{-1}. It is expected that very few real

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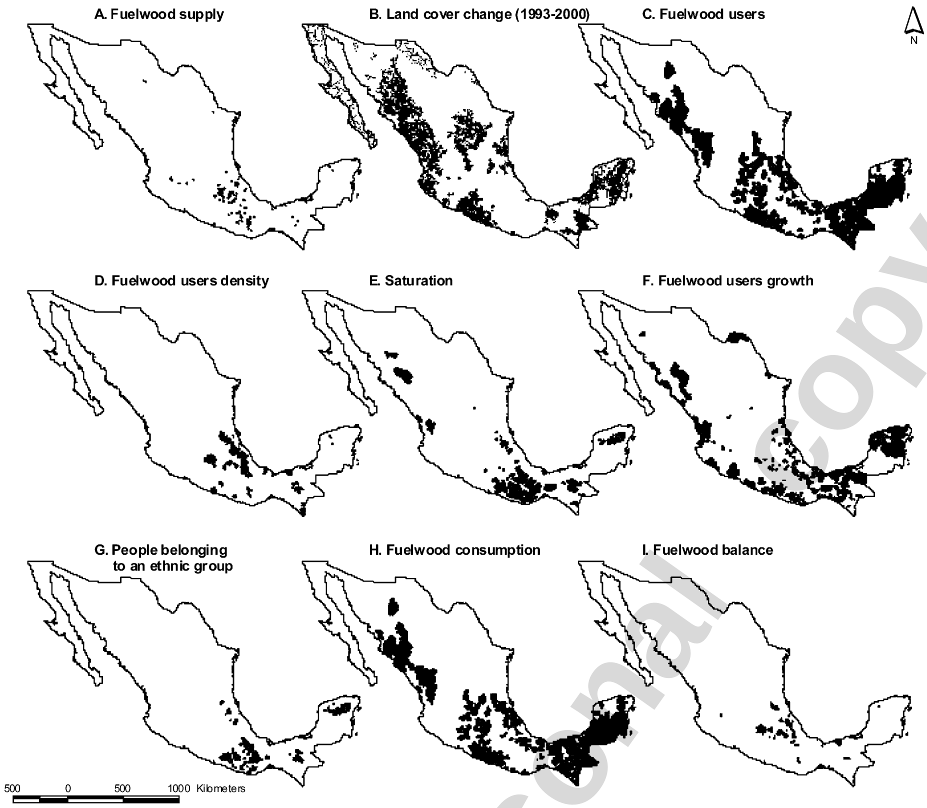

Fig. 2. Spatial distribution of high priority counties (HPC) regarding different indicators' real values, Mexico 2000.
Notes: (A) Fuelwood supply (S) = 339 HPC; (B) land cover change (LC) = 232 HPC; (C) fuelwood users (T) = 286 HPC; (D) fuelwood users density (D) = 313 HPC; (E) Saturation (S) = 381 HPC; (F) fuelwood users' growth annual rate (λ) = 329 HPC; people belonging to an ethnic group (I) = 256 HPC; (G) fuelwood consumption (C) = 241 HPC; fuelwood balance (B) = 186 HPC. Fuelwood balance = supply-consumption (see Eq. (9)). Indicators (A), (B), (D) and (I) are shown over accessible counties areas only. Indicators (C), (E), (F), (G) and (H) are shown over total counties areas.

situations could be outside this range, as the maximum assumed value of 1.47 Mg ha^{-1} is close to the average productivity set for tropical deciduous primary forests (see Table 1).

4.3. *Net CO_2 emissions from non-renewable fuelwood use by the residential sector*

We estimated that approximately 0.7 Tg y^{-1} of FW, which represent 4% of total consumption, are burned in a non-renewable way in Mexico, releasing 1.3 Tg of CO_2 to the atmosphere (Fig. 7). When considering maximum per capita FW consumption and minimum accessible areas, this value rises to 3.2 Tg CO_2 y^{-1} (9% of FW consumption). Our estimates represent from 0.3% to 0.6% of total CO_2 emissions for Mexico in 2002 (493 Tg CO_2 y^{-1} [76]) and from 1.3% to 3.2% of CO_2 emissions reported from land use, land use change and forestry (LULUCF) activities (100 Tg CO_2 y^{-1} [76]).

Preliminary in field estimates of greenhouse gas emissions in the Purhepecha region of Michoacan State (Johnson et al., 2007 comm. pers.), would suggest that including additional Kyoto gases methane and nitrous oxide would result in approximately 8-fold increase in emission estimates relative to net-CO_2, based on mean non-renewability estimates from *WISDOM*. Inclusion of other greenhouse species carbon monoxide and non-methane hydrocarbons would result in a factor 12.5 increase in emissions based on mean renewability estimates. Estimating non-renewability of residential fuel wood is of critical importance, therefore, in assessment of emissions from this sector, since the differences in emissions estimates between non-renewable and renewable are of such magnitude that they frequently outweigh differences in stove type [77].

5. Discussion

Before conducting the present analysis, Mexican data about FW consumption and supply was scattered through the forestry, energy and census agencies. Following the *WISDOM* methodology allowed to consistently integrate this information into a flexible and updatable GIS platform (i.e. geo-database), and to show results in a spatially-explicit way.

It has been recognized that FW supply and demand assessments must deal with spatially heterogeneous patterns (i.e. site-specificity) to avoid mistaken conclusions

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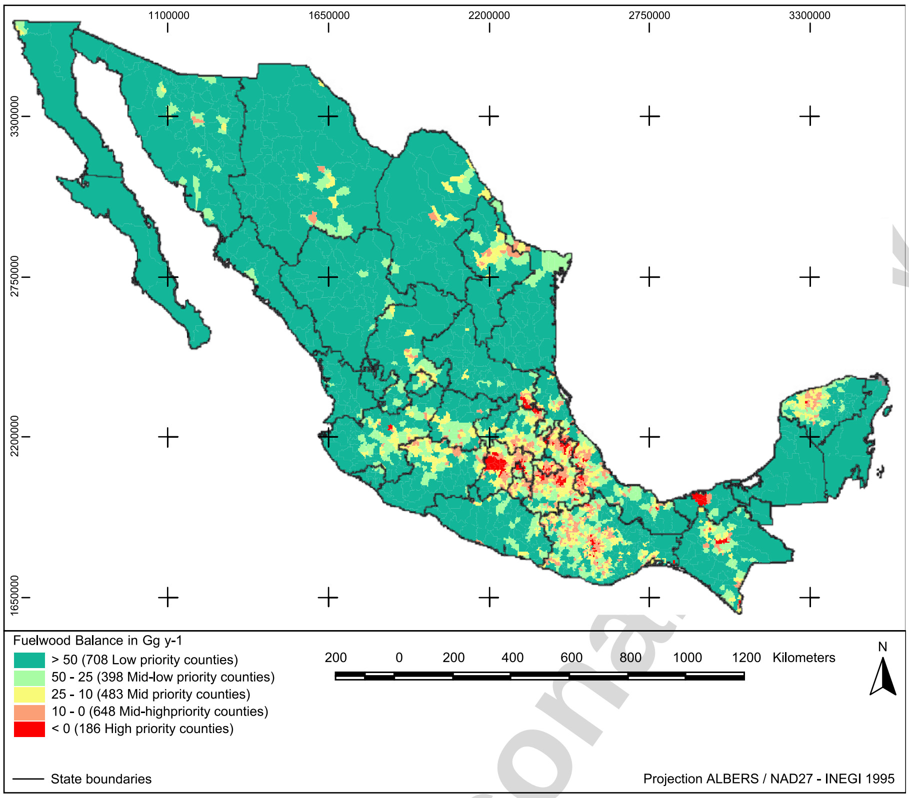

Fig. 3. Fuelwood balance between fuelwood supply and demand, Mexico 2000.

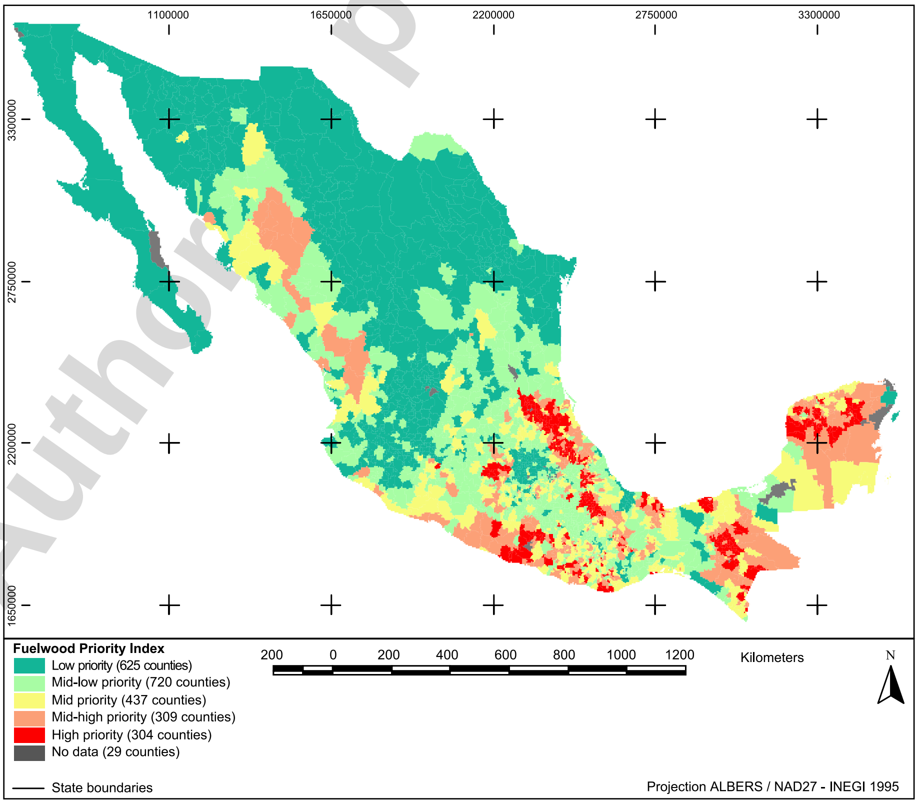

Fig. 4. Priority counties in terms of fuelwood use and availability of fuelwood resources, Mexico 2000.

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Table 8
Main characteristics (mean and standard error) of priority groups according to indicators used in the FPI

FPI group	Land cover change (1993–2000) (L_C) ($Gg\,y^{-1}$)		FW users (T) in number of users		FW users' density (D) in users ha^{-1}		Saturation (SAT) in percentages		FW users' growth (1990–2000) (λ) in percentages		People belonging to an ethnic group (I) in percentages		FW balance (B) ($Gg\,y^{-1}$)	
High priority	−0.6	*0.08*	18,994	*1166*	1.03	*0.05*	84%	*0.9%*	1.5%	*0.1%*	54.7%	*1.7%*	20.0	*2.0*
Mid-high priority	−1.6	*0.24*	15,361	*909*	0.47	*0.02*	75%	*1.3%*	0.8%	*0.1%*	36.8%	*1.8%*	97.0	*13.8*
Mid-priority	−0.6	*0.11*	10,292	*555*	0.42	*0.02*	62%	*1.3%*	−0.3%	*0.1%*	23.1%	*1.4%*	60.1	*8.0*
Mid-low priority	−0.7	*0.08*	6554	*261*	0.23	*0.01*	46%	*1.0%*	−1.9%	*0.1%*	5.0%	0.4%	68.0	*4.9*
Low priority	−0.5	*0.06*	3015	*227*	0.06	*0.00*	12%	*0.5%*	−4.3%	*0.1%*	0.9%	0.1%	83.4	*5.3*

Notes: Standard errors in *italics*.

Table 9
Main characteristics (mean and standard error) of priority groups according to selected variables of interest

FPI group	INEGI welfare index[a]		FW consumption ($Gg\,y^{-1}$)		FW supply ($Gg\,y^{-1}$)		Net CO_2 emissions ($Gg\,CO_2\,y^{-1}$)		Ratio between rural/urban population	
High priority	1.96	*0.07*	17.2	*1.1*	36.7	*2.5*	3.0	*0.7*	2.36	*0.24*
Mid-high priority	2.45	*0.08*	13.8	*0.9*	109.6	*14.1*	0.6	*0.3*	1.85	*0.19*
Mid-priority	3.11	*0.08*	9.0	*0.5*	69.0	*8.2*	0.3	*0.1*	1.25	*0.11*
Mid-low priority	3.64	*0.06*	5.7	*0.2*	72.5	*5.0*	0.1	*0.0*	1.19	*0.07*
Low priority	5.43	*0.05*	2.6	*0.2*	85.2	*5.4*	0.0	*0.0*	0.64	*0.04*

Notes: Standard errors in *italics*. [a]This variable, from the INEGI census, summarizes more than 20 socioeconomic variables and gives an average measure by county of the population welfare. The lower level of welfare is "1", while the highest is "7".

Table 10
States ranked according to the percentage of their area covered by high priority counties (HPC)

States	State's area covered by high priority counties (ha and percentages)		Number of counties
Yucatan	1,300,812	33%	37
Guerrero	1,121,196	18%	16
Puebla	574,512	17%	47
Chiapas	1,193,200	16%	35
Veracruz	1,114,144	16%	55
Hidalgo	292,952	14%	13
Estado de Mexico	282,792	13%	8
Oaxaca	745,744	8%	72
Tabasco	203,176	8%	4
San Luis Potosi	338,112	6%	12
Campeche	354,276	6%	2
Michoacan	96,132	2%	3
Total	7,617,048	4%	304

based on aggregated averages [3,22,59,61,64]. For example, we estimated that the national FW balance in Mexico for the year 2000 was very positive ($165\,Tg\,y^{-1}$), however, 186 counties mostly distributed within the Central-East region of Mexico, have negative balances (13 of them with a deficit of more than $10\,Gg\,y^{-1}$) (Fig. 3 and Table 7).

As seen from Fig. 4, spatially heterogeneous patterns not only are a characteristic of each indicator's distribution, but to the FPI categorization as well. Identifying FW *hot spots* from a national perspective allows focusing on target areas that deserve further attention. Similar approaches are been developed by *WISDOM* case studies in selected European, Asian and African countries [23–26], and by other relevant woodfuels spatial analyses as the ones developed by Top et al. in Cambodia [61,64].

Further analyses should be conducted over identified FW *hot spots*, based on more accurate and region-oriented basic data assumptions. Multi-scale analyses are a promising option for developing *WISDOM* beyond national-wide analyses. Scarce financial and human resources for the design and implementation of appropriate policies and measures to promote a sustainable use of woodfuels should be mostly directed over FW *hot spots*, identified from multi-scale approaches.

The applicability of *WISDOM* is not restricted to the present analysis, as it allows ranking counties according to any set of predefined criteria concerning environmental, social or economic issues. For example, it can be used to develop future scenarios of the FW situation in the country [24], to help identify population at risk from indoor air pollution by FW burning within households, or to establish target areas for forest management or restoration efforts oriented to FW production.

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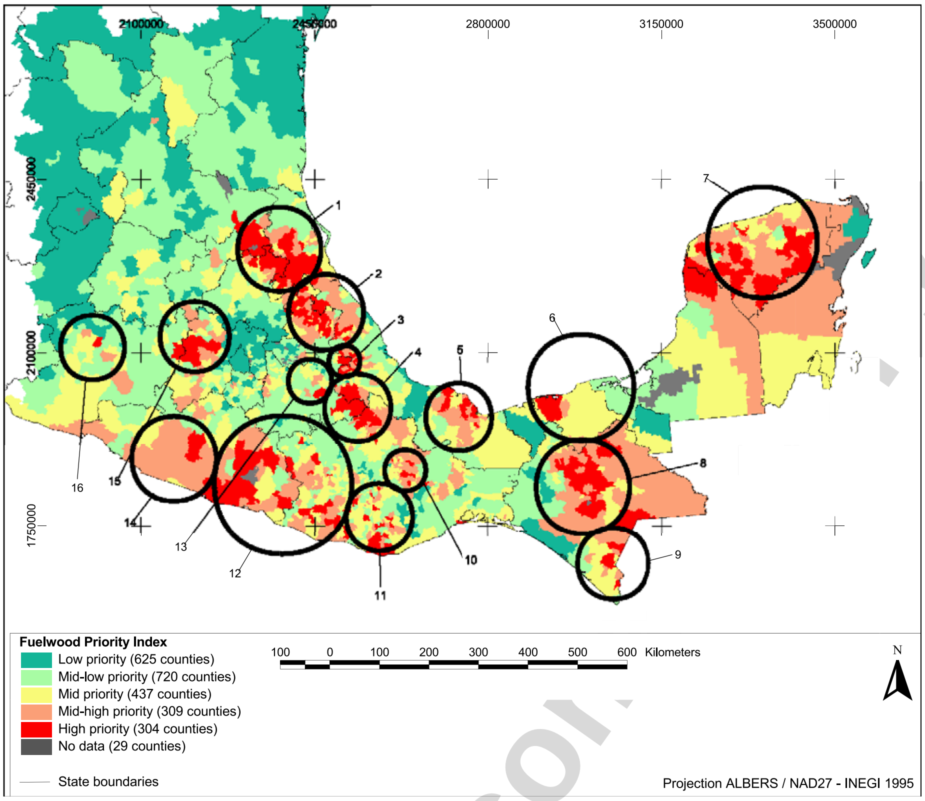

Fig. 5. Clusters of high priority counties (HPC), Mexico 2000.

Notes: Ethnic groups names in *italics*. (1) Huasteca Potosina/Veracruzana and counties from northern Hidalgo (majority of population belonging to *Nahuas* and *Huastecos* ethnic groups); (2) *Nahua* area at the northern sierra of Puebla and *Totonaca* counties from Veracruz gulf coasts; (3) Veracruz center counties; (4) *Nahua* area at "Orizaba–Cordoba" ravine in the Oaxaca–Puebla border, *Mazateco* area at northern Puebla and Tehuacan valley; (5) Los Tuxlas Biosphere Reserve; (6) *Chontal* area of Tabasco and Villahermosa city northern counties; (7) Yucatan north and center counties; (8) Chiapas highlands (*Tzotzil* area); (9) Soconusco Region (*Mam* area); (10) *Mixe* area at Oaxaca; (11) *Zapoteca* area at southern Oaxaca; (12) *Mixteca* area at Guerrero y Oaxaca; (13) Puebla center counties; (14) South Guerrero counties (pacific coast), (15) *Otomi* and *Mazahua* area at Estado de Mexico; (16) *Purhepecha* Region in Michoacan State.

6. Conclusions and future research directions

The analysis conducted in Mexico confirmed that the FW situation is very heterogeneous within the country; therefore broad generalizations about the impacts of FW use are wrong. The *WISDOM* analysis for Mexico established a comprehensive, flexible and updatable GIS platform that allowed ranking counties, according to a set of seven indicators concerning environmental, social and economic issues.

More accurate spatial analyses over priority areas identified at the national scale are needed in order to articulate the national/regional heterogeneity of FW supply/demand patterns, with local situations. These results will help in designing woodfuel planning strategies, as local-oriented projects (e.g. woodstoves, re-growth management, multi-purpose plantations, etc.) can be soundly established according to each specific situation. At present, a detailed spatial analysis is been conducted over four *hot spots* identified in the *WISDOM* analysis for Mexico at the national scale.

Based on our WISDOM results for Mexico, we can now get a more precise and spatial-explicit estimate of the net CO_2 emissions from non-renewable FW use at the country level, which is a key step in estimating the actual impacts of this fuel on total country emissions. Once emission factors from non-CO_2 gases associated to FW burning are available for Mexico, estimates of the overall impact on GHG emissions at the national level could be obtained. In addition, identifying those places where fuelwood is harvested renewably and not renewably will help deriving regional baselines on clean development mechanisms (CDM) projects.

Further *WISDOM* analyses for Mexico should include both FW demand coming from small industries and charcoal demand coming from peri-urban centers. Although there are no national statistics about these sectors, as they belong to the informal economy, assumptions on consumption amounts and extraction patterns could possibly be derived from case studies developed in the country.

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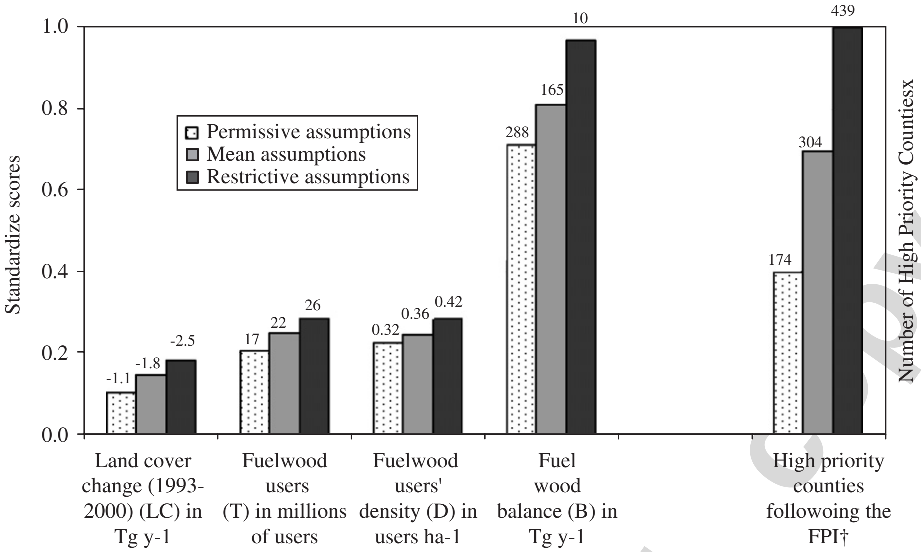

Fig. 6. National average standardized scores of indicators subject to permissive and restrictive assumptions.
Notes: Bars height corresponds to standardized scores. Values over bars corresponds to indicators' real values (prior to standardization, see also Table 7). (†) Values over bars correspond to the number of HPC following each perspective (permissive or restrictive); bars height does not correspond with 0–1 scale on the left. Note that FW supply and consumption were not included as they were not standardized separately, but as FW balance. Saturation, FW users' growth, and the percentage of population belonging to an ethnic group were not included as they are not subject to uncertainties assumptions. Permissive assumptions were based on: (1) maximum FW productivities, (2) maximum accessible areas, (3) only exclusive users reported by INEGI (i.e. mixed users were not considered), and (4) minimum per capita FW consumption. Restrictive assumptions were based on: (1) minimum FW productivities, (2) minimum accessible areas, (3) maximum mixed users estimation based on Diaz (2000) and (4) maximum per capita FW consumption. Mean assumptions were based on: (1) average FW productivities, (2) maximum accessible areas (there are no average accessible areas, see Section 3.1.3.3), (3) average mixed users estimation based on Diaz (2000) and (4) average per capita FW consumption.

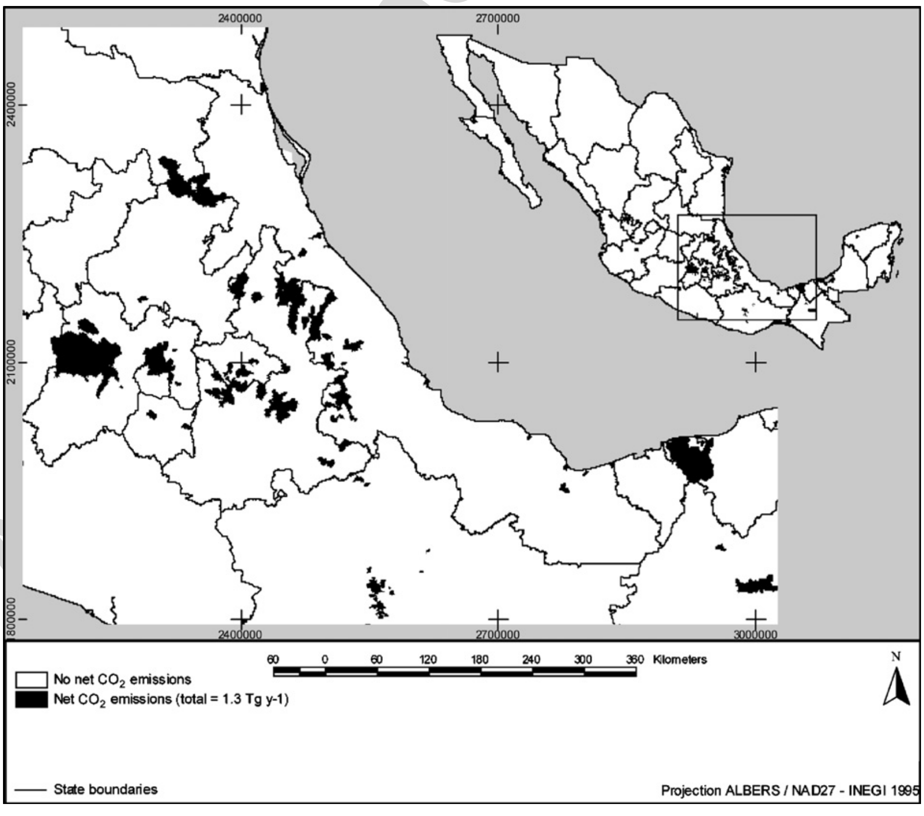

Fig. 7. Estimated net CO_2 emissions from the non-renewable use of fuelwood, Mexico 2000.

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Appendix A

Fig. 8 shows linear value functions for six of the seven indicators used in the construction of the FPI. Saturation was not included as real values of this indicator vary between 0 and 1. Linear value functions express the relation between the indicator real value (X axis) and the corresponding value score between 0–1 (Y axis). Break points (arrows) were set to avoid non representative value functions due to wide ranges in indicators' real values (Table 6). Indicators' real values beyond break points

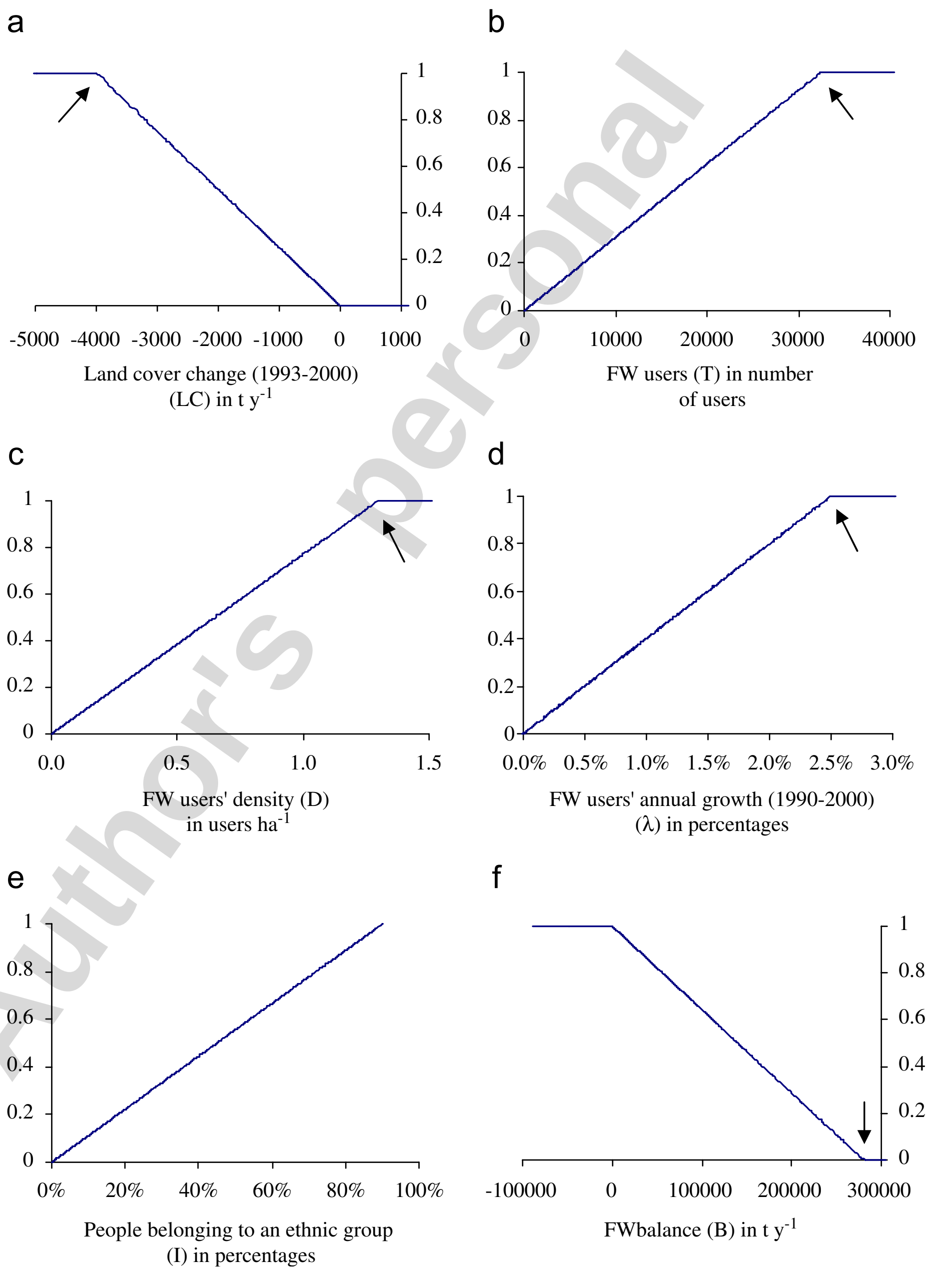

Fig. 8.

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accounts for 5% of counties analyzed. A. Land cover change positive values were all scored as 0. F. Break point was set for positive values, as balance negative real values were all scored as 1 (186 counties, accounting for 8% of counties analyzed).

References

[1] Trossero MA. Wood energy: the way ahead. Unasylva 2002;53(211): 3–12.

[2] IEA (International Energy Agency). Energy and poverty. In: World energy outlook. Paris: International Energy Agency; 2002.

[3] Masera O, Ghilardi A, Drigo R, Trossero MA. *WISDOM*: a GIS-based supply demand mapping tool for woodfuel management. Biomass and Bioenergy 2006;30:618–37.

[4] Eckholm E. The other energy crisis: firewood. Worldwatch paper 1. Washington, DC: Worldwatch Institute; 1975.

[5] FAO (Food and Agriculture Organization of the United Nations). Forestry for local community development. Forestry paper 7. Rome: FAO; 1978.

[6] FAO (Food and Agriculture Organization of the United Nations). Map of the fuelwood situation in the developing countries. Unasylva supplement. Rome: FAO; 1981.

[7] De Montalembert MR, Clement J. Fuelwood supplies in the developing countries. Forestry paper no. 42. Rome: FAO; 1983.

[8] Arnold M, Köhlin G, Persson R, Shepherd G. Fuelwood revisited: what has changed in the last decade? Occasional paper no. 39. Bogor Barat, Indonesia: Center for International Forestry Research (CIFOR); 2003.

[9] Arnold M, Köhlin G, Persson R. Woodfuels, livelihoods, and policy interventions: changing perspectives. World Development 2006;34: 596–611.

[10] Foley G. Exaggerating the Sahelian woodfuel problem? Ambio 1987; 16(6):367–71.

[11] Leach M, Mearns R. Beyond the woodfuel crisis: people, land and trees in Africa. London: Earthscan Publications; 1988.

[12] Lelé S. Degradation, sustainability, or transformation? A case study of villager‘s use of forest land in the Malnaad Region of Uttara Kannada District, India. PhD thesis. Berkeley: University of California; 1993.

[13] Masera O. Socioeconomic and environmental implications of fuel-wood use dynamics and fuel switching in rural Mexico. PhD thesis. Berkeley: University of California; 1994.

[14] Mahapatra AK, Mitchell CP. Biofuel consumption, deforestation, and farm level tree growing in rural India. Biomass and Bioenergy 1999;17:291–303.

[15] RWEDP (Regional Wood Energy Development Programme in Asia). Regional study on wood energy: today and tomorrow in Asia. Field document no. 50. Regional wood energy development programme in Asia GCP/RAS/154/NET. Bangkok, Thailand: FAO; 1997.

[16] RWEDP (Regional Wood Energy Development Programme in Asia). Basics of Wood energy planning: a manual. RWEDP report no. 64. Regional wood energy development programme in Asia GCP/RAS/154/NET. Bangkok, Thailand: FAO; 2000.

[17] Masera O. Uso y Conservación de Energía en el Sector Rural: El caso de la leña. Documento de Trabajo no. 21. Pátzcuaro, México: GIRA AC; 1996.

[18] WEC (World Energy Council). The challenge of rural energy poverty in developing countries. London: WEC; 1999.

[19] MNP (Netherlands Environmental Assessment Agency in English). Emission Database for Global Atmospheric Research (EDGAR). *EDGAR 3.2 Fast Track 2000* emission dataset in 2000: ⟨http://www.mnp.nl/edgar/model/v32ft2000edgar/edgv32ft-ghg/edgv32ft-co2.jsp⟩. Downloadable summary table in excel format by sources and regions (last visited on February 2007).

[20] Bailis R, Ezzati M, Kammen DM. Greenhouse gas implications of household energy technology in Kenya. Environmental Science Technology 2003;37(10):2051–9.

[21] Bond T, Venkataraman C, Masera O. Global atmospheric impacts of residential fuels. Energy for Sustainable Development 2004;VIII(3): 20–32.

[22] Masera O, Drigo R, Trossero MA. Woodfuels integrated supply/demand overview mapping (WISDOM): a methodological approach for assessing woodfuel sustainability and support wood energy planning. FAO-EC partnership programme; wood energy programme—FAO Forestry Department. Rome: FAO; 2003. Available from the Internet at: ⟨http://www.fao.org/documents/show_cdr.asp?url_file = /DOCREP/005/y4719e/y4719e00.htm⟩ (last visited on February 2007).

[23] Drigo R. WISDOM Slovenia: analysis of spatial woodfuel production–consumption patterns in Slovenia. Consultancy report FAO/Government of Slovenia project "Supply and utilization of bioenergy to promote sustainable forest management" TCP/SVN/2901. Rome: FAO; 2004.

[24] Drigo R. WISDOM Senegal: Analysis of woodfuel production–consumption patterns in Senegal. Consultancy report, FAO wood energy programme. Rome: FAO; 2004.

[25] Drigo R. East Africa WISDOM - Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) methodology - spatial woodfuel production and consumption analysis of selected African countries. FAO Wood Energy Programme. Rome: FAO; 2006. Available from the Internet at: http://www.fao.org/docrep/009/j8227e/j8227e00.HTM (last visited on March 2007).

[26] Drigo R. Wood-energy supply/demand scenarios in the context of poverty mapping. A WISDOM case study in Southeast Asia for the years 2000 and 2015. FAO Wood Energy Programme (FOPP) and Poverty Mapping Project (SDRN). Rome: FAO; 2007 (in press).

[27] INEGI (Instituto Nacional de Estadística, Geografía e Informática). XII Censo General de Población y Vivienda, 2000. México DF: INEGI; 2000.

[28] Díaz R. Consumo de leña en el sector residencial de México: evolución histórica y emisiones de CO_2. Tesis de Maestría. México DF: Facultad de Ingeniería, UNAM; 2000.

[29] Masera O. Deforestación y degradación forestal en México. Documento de trabajo no. 19. Pátzcuaro, México: GIRA AC; 1996.

[30] Masera O, Navia J, Arias T, Riegelhaupt E. Patrones de Consumo de Leña en Tres Micro-regiones de México: Síntesis de Resultados. Proyecto FAO/MEX/TCP/4553(A). Pátzcuaro, México: GIRA AC; 1997.

[31] Del Amo Rodríguez S. (coord.). La leña: el energético rural en tres micro-regiones del sureste de México. PROAFT AC. México DF: Plaza y Valdéz Editores; 2002.

[32] Puentes V. Impacto del consumo de leña en el bosque de Santa Fe de la Laguna, Michoacán. Tesis de Licenciatura. México DF: Facultad de Ciencias, UNAM; 2002.

[33] Kaale BK. Traditional fuels. In: Pastzor J, Kristoferson LA, editors. Bioenergy and the environment. Environment Institute of the United Nations Environment Programme UNEP. Oxford: Westview Press; 1990.

[34] Palacio JL, Bocco G, Velásquez A, Mas JF, Takaki F, Victoria A, et al. La condición actual de los recursos forestales en México: resultados del Inventario Forestal Nacional 2000. Boletín del Instituto de Geografía. UNAM 2000;43:183–203.

[35] INEGI (Instituto Nacional de Estadística, Geografía e Informática). XI Censo General de Población y Vivienda, 1990. México DF: INEGI; 2000.

[36] INEGI (Instituto Nacional de Estadística, Geografía e Informática). Geo-referenced map from mexican municipalities. México DF: INEGI; 1995.

[37] Malhi YR, Baker TR, Phillips OL, Almeida S, Alvarez E, Arroyo L, et al. The above-ground coarse wood productivity of 104 Neotropical forest plots. Global Change Biology 2004;10:563–91.

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[38] Clark DA, Brown S, Kicklighter DW, Chambers JQ, Thomlinson JR, Ni J, et al. Net primary production in tropical forests: an evaluation and synthesis of existing field data. Ecological Applications 2001;11(2):371–84.
[39] Martínez-Yrízar A, Maass LA, Pérez-Jiménez E, Sarukhán J. Net primary productivity of a tropical deciduous forest ecosystem in western Mexico. Journal of Tropical Ecology 1996;8:87–96.
[40] SARH (Secretaría de Agricultura y Recursos Hídricos). Inventario Forestal Nacional Periódico (IFN). Memoria Nacional de la Subsecretaría Forestal y de Fauna Silvestre. México DF: Secretaría de Agricultura y Recursos Hidráulicos; 1994.
[41] Brown S. Estimating biomass and biomass change of tropical forests: a primer. FAO forestry paper—134. Department of Natural Resources and Environmental Sciences. University of Illinois. Urbana, Illinois, USA. A forest resources assessment publication. Rome: FAO; 1997.
[42] Reyes G, Brown S, Chapman J, Lugo AE. Wood densities of tropical tree species. General technical report SO-88, Southern Forest Experiment Station. New Orleans, LA, USA: USDA Forest Service; 1992.
[43] Cannell MGR. Dry matter partitioning in tree crops. In: Cannell MGR, Jackson JE, editors. Attributes of plant trees as crop plants Huntingdon. United Kingdom: Institute of Terrestrial Ecology; 1985.
[44] Cannell MGR. Woody biomass of forests stands. Forest Ecology and Management 1984;8:299–312.
[45] Cannell MGR. World biomass and primary production data. Natural Environment Research Council, Institute of Terrestrial Ecology. Penicuik, Midlothian, Scotland: Academic Press; 1982.
[46] Návar J, Méndez E, Dale V. Estimating stand biomass in the Tamaulipan thornscrub of northeastern Mexico. Annals of Forest Science 2002;59:813–21.
[47] Návar J, Nájera J, Jurado E. Preliminary estimates of biomass growth in the Tamaulipan thornscrub in north-eastern Mexico. Journal of Arid Environments 2001;47:281–90.
[48] Huenneke LF, Anderson J, Remmenga M, Schlesinger H. Desertification alters patterns of aboveground net primary production in Chihuahuan ecosystems. Global Change Biology 2002;8:247–64.
[49] Saenger P, Snedaker SC. Pantropical trends in mangrove above-ground biomass and annual litterfall. Oecologia 1993;96:293–9.
[50] Day JW, Coronado-Molina C, Vera-Herrerra FR, Twilley R, Rivera-Monroy VH, Álvarez-Guillen H, Day R, et al. A 7-year record of above-ground net primary production in a southeastern Mexican mangrove forest. Aquatic Botany 1996;55:39–60.
[51] Day JW, Conner W, Ley-Lou F, Day RH, Navarro AM. The productivity and comparison of mangrove forests, Laguna de Terminos, Mexico. Aquatic Botany 1987;27:267–84.
[52] Ross MS, Ruiz PL, Telesnicki GJ, Meeder JF. Estimating above-ground biomass and production in mangrove communities of Biscayne National Park FL, USA. Wetlands Ecology and Management 2001;9:27–37.
[53] Jensen AM. Evolution des données sur les ressources ligneuses au Burkina Faso, Gambie, Mali, Niger et Sénégal. In: Examen des politiques, stratégies et programmes du secteur des énergies traditionnelles. Washington DC: Banque Mondiale; 1995.
[54] Sánchez Gonzáles MC. Uso y manejo de la leña en X-uilub, Yucatán. Tesis de Maestría. México DF: Facultad de Ciencias, UNAM; 1993.
[55] Monroy Ortiz C. La leña como recurso energético, implicaciones ecológicas y etnobotánicas. Tesis de Licenciatura. México DF: Facultad de Ciencias, UNAM; 1997.
[56] Negrón Pérez E. Etnobotánica y aspectos ecológicos de las plantas útiles de Santiago Quiotepec, Cuicatlán, Oaxaca. Tesis de Licenciatura. México DF: Facultad de Ciencias; 2002.
[57] Rangel S, Lemus R. Aspectos etnobotánicos y ecológicos de los recursos vegetales entre los Ixcatecos de Santa María Ixcatlán, Oaxaca, México. Tesis de Licenciatura. Morelia, México: Facultad de Biología, UMSNH; 2002.
[58] Tovar MR. Uso de leña y su impacto en comunidades de la Región Purhépecha, Michoacán, México. Tesis de Maestría. Turrialba, Costa Rica: CATIE; 2004.
[59] Millington AC, Ryan P, Douglas, Critchley RW. Estimating woody biomass in Sub-Saharan Africa. Washington DC: World Bank; 1994.
[60] Marble DF, Geographic information system technology and decision support systems. In: Proceedings of the XXXII annual Hawaii international conference on system sciences. Institute of Electrical and Electronics Engineers, Inc. ⟨www.ieee.org⟩, Hawaii, 1998.
[61] Top N, Mizoue N, Ito S, Kai S. Spatial analysis of woodfuel supply and demand in Kampong Thom Province, Cambodia. Forest Ecology and Management 2004;194:369–78.
[62] INEGI (Instituto Nacional de Estadística, Geografría y Censos). ⟨http://www.inegi.gob.mx/prod_serv/contenidos/espanol/simbad/default.asp?c=73⟩ (last visited on February 2007).
[63] INAFED (Instituto Nacional para el Federalismo y el Desarrollo Municipal). ⟨http://www.e-local.gob.mx/wb2/ELOCAL/ELOC_Los_ultimos_municipios_creados⟩, and ⟨http://www.inafed.gob.mx/wb2/⟩ (last visited on February 2007).
[64] Top N, Mizoue N, Ito S, Kai S, Nakao T, Ty S. Re-assessment of woodfuel supply and demand relationships in kampong Thom Province. Cambodia. Biomass and Bioenergy 2006;30:134–43.
[65] FAO (Food and Agriculture Organization of the United Nations). Survey of tropical forest cover and study of change processes. Forestry paper no. 130. Rome: FAO; 1996.
[66] Mas JF, Palacio JL, Velázquez A, Bocco G. Evaluación de la confiabilidad temática de bases de datos cartográficas. Memorias del I Congreso Nacional de Geomática. Guanajuato, Mexico, 26–28 de septiembre de 2001. ⟨http://www.igeograf.unam.mx/ua_morelia/_private/2001/eval_conf_gto/evalconf_congreso.htm⟩ (last visited on February 2007).
[67] Mlambo D, Huizing H. Household responses to fuelwood scarcity: a case study of two villages in Zimbawe. Land Degradation & Development 2004;15:271–81.
[68] Mahiri IO. Rural household responses to fuelwood scarcity in Nyando District, Kenya. Land Degradation & Development 2003;14:163–71.
[69] Hosier R. Household energy consumption in Kenya. Ambio 1985;14:225–7.
[70] Geneletti D. A GIS-based decision support system to identify nature conservation priorities in an alpine valley. Land Use Policy 2004;21:149–60.
[71] Beinat E. Value functions for environmental management. Dordrecht: Kluwer; 1997.
[72] Janssen R. On the multi-criteria analysis in environmental impact assessment. Journal of Multi-Criteria Decision Analysis 2001;10:101–9.
[73] Smith KR, Uma R, Kishore VVN, Zhang J, Joshi V, Khalil MAK. Greenhouse implications of householdstoves: an analysis for India. Annual Review of Energy and the Environment 2000;25:741–63.
[74] Broadhead J, Bahdon J, Whiteman A. Woodfuel consumption modelling and results. Annex 2. In: Past trends and future prospects for the utilization of wood for energy. Working paper GFPOS/WP/05, global forest products outlook study. Rome: FAO; 2001.
[75] SENER (Secretaría de Energía de México). Balance Nacional de Energía. ⟨http://sie.energia.gob.mx/sie⟩ (last visited on February 2007).
[76] SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales). México: Tercera Comunicación Nacional ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. México DF: INE-SEMARNAT; 2006. ⟨http://ine.gob.mx/publicaciones/descarga.html?cv_pub=489&tipo_file=pdf&filename=489⟩ (last visited on February 2007).
[77] Edwards RD, Smith KR, Zhang J, Ma Y. Implications of changes in household stoves and fuel use in China. Energy Policy 2004;32:395–411.