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A GIS-based methodology for highlighting fuelwood supply/demand imbalances at the local level: A case study for Central Mexico

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ABSTRACT

When fuelwood is harvested at a rate exceeding natural growth and inefficient conversion technologies are used, negative environmental and socio-economic impacts, such as fuelwood shortages, natural forests degradation and net GHG emissions arise. In this study, we argue that analyzing fuelwood supply/demand spatial patterns require multi-scale approaches to effectively bridge the gap between national results with local situations. The proposed methodology is expected to help 1) focusing resources and actions on local critical situations, starting from national wide analyses and 2) estimating, within statistically robust confidence bounds, the proportion of non-renewable harvested fuelwood. Starting from a previous work, we selected a county-based fuelwood hot spot in the Central Highlands of Mexico, identified from a national wide assessment, and developed a grid-based model in order to identify single localities that face concomitant conditions of high fuelwood consumption and insufficient fuelwood resources. By means of a multi-criteria analysis (MCA), twenty localities, out of a total of 90, were identified as critical in terms of six indicators related to fuelwood use and availability of fuelwood resources. Fuelwood supply/demand balances varied among localities from -16.2 ± 2.5 Gg y^{-1} to 4.4 ± 2.6 Gg y^{-1}, while fractions of non-renewable fuelwood varied from 0 to 96%. These results support the idea that balances and non-renewable fuelwood fractions (mandatory inputs for Clean Development Mechanism (CDM) cookstoves projects) must be calculated on a locality by locality basis if gross under or over-estimations want to be avoided in the final carbon accounting.

1. Introduction

About 2.5 billion people in developing countries rely on traditional and low-tech uses of biomass to meet their residential energy needs, predominantly cooking [1]. On current trends, this number will increase to 2.7 billion by 2030 [1]. Global fuelwood consumption in 2000 reached 2.3 km^3; accounting for roughly 60% of all the wood harvested that year. For the group of developing countries this proportion rises to 80% [2]. This is to say, energy is the main application of woody biomass worldwide.

When resources are harvested in a renewable way and efficient conversion technologies are used, woody biomass represents a major option among renewable energy sources

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[3–6]; including the residential sector of developing countries [7]. On the contrary, clear negative environmental and socio-economic impacts arise from the non-sustainable use of fuelwood for residential purposes:

- Fuelwood shortages: depletion of fuelwood resources around localities and peri-urban areas directly affects the poor: a) extending even more the time consuming task of fuelwood collection, b) increasing fuelwood prices and c) under extreme conditions, putting into risk a basic human need, such as food [1,8].
- Natural forest degradation: although fuelwood extraction for residential purposes is not a major cause of deforestation, tree removal is likely to occur in localized areas, as for example in large and growing peri-urban areas [9]. Moreover, wood removal for fuel only at a low but constant rate may have negative impacts on the structure of natural forests [10].
- Net GHG emissions: interest on potential fuelwood deficits has grown recently due to their contribution to global GHG emissions. The non-renewable harvest and burning of biomass by the residential sector may account for about 4% of global CO_2 emissions [11,12].

Non-sustainable fuelwood situations are however geographically patchy, and their distribution depends on very site-specific variables, such as wood supplies, land cover change trends, accessibility restrictions, fuelwood consumption patterns, cultural basis, among others [8,13,14]. Then, how can localized situations where fuelwood is extracted and used on a non-sustainable way be identified starting from a national wide perspective?

As a first methodological response to this problem, Masera, Drigo and Trossero developed the Woodfuels Integrated Supply/Demand Overview Mapping WISDOM approach in 2003, a collaborative effort between the National Autonomous University of Mexico (UNAM) and the Food and Agriculture Organization of the United Nations (FAO) [7,15]. WISDOM is a spatial-explicit planning tool for highlighting and determining woodfuel priority areas or woodfuel hot spots at national scales. To identify these critical areas or hot spots, basic spatial units (BSUs) of analysis (often corresponding to second administrative units e.g. counties) are ranked into priority categories, by analyzing relevant interactions over a set of socio-economic and environmental criteria and indicators, directly or indirectly related to woodfuels' supply and demand patterns.

So far, WISDOM has been conducted in several countries and regions: Mexico [16]; East Africa [17]; South-east Asia [18]; Brazil [19]; Senegal [20]; and Slovenia [21]. All these assessments succeeded in identifying fuelwood hot spots from national or supra-national perspectives, however, the hot spots spatial detail is still insufficient for identifying differences or priorities within selected BSUs, i.e. at the local level, which are necessary for directing concrete actions.

We argue that analyzing fuelwood supply/demand spatial patterns through multiple scales effectively helps in bridging this gap by articulating the national WISDOM results with local situations. The proposed new methodology is expected to help 1) focusing resources and/or actions on those local situations that face concomitant conditions of high fuelwood consumption and insufficient fuelwood resources, starting from a national wide perspective and 2) estimating the proportion of non-renewable harvested fuelwood, a key value for deriving Clean Development Mechanism (CDM) baselines for non-renewable fuelwood consumption in business as usual (BAU) and project scenarios.

We apply the WISDOM methodology, at a locality by locality level, to the *Purhepecha* Region in *Michoacán* State in Central Mexico (19° 32′N, 101° 50′W at the center), a fuelwood hot spot previously identified in the national assessment [16]. As in the national assessment the goal was to: (1) identify hot spots in terms of residential fuelwood use and availability of fuelwood resources for the year 2000, and (2) estimate the fraction extracted on a non-renewable basis for the same year.

2. Fuelwood extraction and use patterns in the study area

The *Purhepecha* Region has an area of 653 074 ha, from which 400 183 ha were natural forests in the year 2000. Forests consist mostly of pines, oaks and pine–oak associations. Dominant land use classes are mainly represented by rainfed agriculture and fruit crops (mostly avocados) (Fig. 1).

Residential fuelwood use in the *Purhepecha* Region is characterized by self-gathering practices and the widespread use of low-tech devices such as three stone fires. When urban grids grow larger, local traders selling fuelwood from the cities' surroundings become more frequent. In addition to its residential use for cooking and space and water heating, fuelwood is also employed in small industries as pottery, brick making, and *tortilla* and bread cooking. No consistent statistics exist however for this sector as all the mentioned enterprises belong to the informal economy.

Two types of residential fuelwood users exist: those exclusively relying on fuelwood as their only energy source for the household (exclusive users), and those that use fuelwood in combination with Liquefied Petroleum Gas (LPG) (mixed users). Census data only report exclusive users while mixed users are estimated based on field surveys. By the year 2000, total population reached 732 594 inhabitants, distributed over 149 420 houses, 787 localities (745 villages and 42 cities) and 19 counties. *Purhepechas* are the dominant ethnic group in the region, accounting for 14% of total population. The number of exclusive fuelwood users was 227 701 in 2000, more than 30% of the total population. Those 90 localities with more than 100 households that used fuelwood in the year 2000 were selected for this study, representing 76% of total fuelwood consumption in the residential sector (172 729 people in 32 920 houses exclusively relying on fuelwood).

Fuelwood gatherers can be divided into three groups: a) walking women and children; b) walking men with or without pack animals; and c) men using motorized vehicles, being this third group the least represented. Women and children collect dead wood from trees in agriculture areas and grasslands, while men using pack animals collect fuelwood from forest areas. Men harvest living trees with axes or chainsaws, cut them into pieces *in situ* and carried out with the help of pack animals and eventually with motorized vehicles. Up to 3 or 4 h

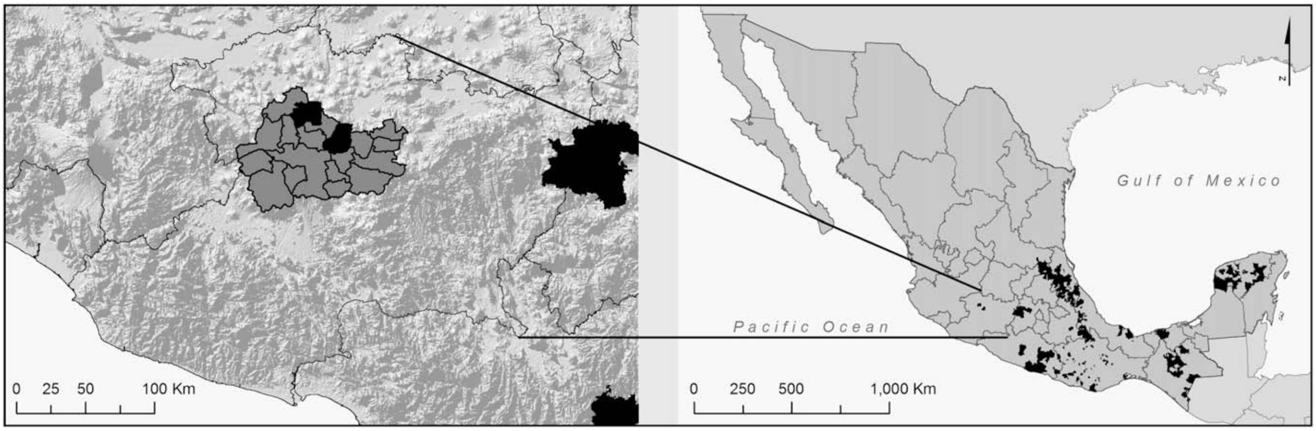

Fig. 1 – Study area: the *Purhepecha* Region. Notes: Black irregular spots in both maps represent fuelwood high priority counties following WISDOMs national assessment [16]. On the map of the left, counties conforming the *Purhepecha* Region (19° 32′N, 101° 50′W at the center) were highlighted in dark grey.

(round trip) are spent by day for collecting fuelwood by any of the three types of gatherers. Oaks are the preferred species for fuelwood given the characteristics of their wood.

3. Methods

Like the national WISDOM, conducting a regional WISDOM analysis involves four main steps [7]: 1) Selection of the basic spatial unit (BSU) of analysis. In this step the map elements which will be ranked are defined, determining the level of spatial aggregation, and consequently, the spatial detail of the priorization output maps. It is needed that BSUs do not overlap, as to avoid double counting. 2) Development of the supply and demand modules. Socio-economic and environmental criteria and indicators related to fuelwood supply and demand are identified and selected. 3) Development of the integration module. Relevant indicators from the supply and demand modules are combined. 4) Selection of priority areas or fuelwood hot spots. At this final stage, a multi-criteria analysis (MCA) linked to a GIS platform is used to identify priorities among the spatial units.

3.1. *Selection of the basic spatial unit (BSU) of analysis by means of accessible areas*

For national or supra-national analyses, the second subnational administrative level of territorial division or Local Administrative Units (LAU) is mostly chosen (e.g. counties, municipalities or districts) [16–21]. In the present regional analysis, which focuses on fuelwood hot spots previously identified, BSUs should correspond to the third sub-national administrative level of territorial division, which in Mexico corresponds to communal, private and federal lands. Unfortunately in Mexico, as in most developing countries, no consistent georeferenced databases exist at this detailed level of administrative territorial division. Non-administrative BSUs were selected instead.

Non-administrative BSUs were defined by estimating accessible or reachable areas around individual localities for two types of fuelwood gatherers: 1) walking fuelwood gatherers, including those ones using pack animals; and 2) fuelwood gatherers using motorized vehicles. Accessible areas around individual localities are defined as the area from which fuelwood gatherers obtain fuelwood i.e. the woodfuelshed, given topographic constraints, means of transport and daily time available for collecting and transporting fuelwood. For a detailed description of the grid-based methodology developed for calculating accessible areas, please refer to the Electronic Annex 1 in the online version of this article. It is worth to mention that calculating fuelwood supply areas are a key step in Kyoto's approved methodology for small-scale CDM project activities [22].

3.2. *Supply module*

The fuelwood supply capacity of an area is a function of: (a) fuelwood stocking and productivity in natural formations and anthropic landscapes; (b) land cover changes, which indirectly affect fuelwood availability; and (c) access to fuelwood supply resources [7,14,23,24]. Following the first two criteria, two poorly correlated indicators were incorporated into the supply module: the annual fuelwood increment which can be sustainably harvested and the annual variations in fuelwood production due to land cover changes between years 1986 and 2000. Access to fuelwood supply resources was already described in the previous step (see Section 3.1). Indicators' values, disaggregated by localities' accessible areas, were calculated through the spatial integration of basic data using ESRI® ArcMap™ 9.2.

The annual fuelwood increment which can be sustainably harvested from each locality accessible area was estimated using the following equation:

$$\mathrm{FWS}_{\upsilon} = \sum_{j=1}^{8} (A_{\upsilon j} \times P_j) \tag{1}$$

where FWS_{υ} is the amount of fuelwood which can be sustainably harvested from each locality accessible area "υ", in Mg y^{-1} (dry matter); $A_{\upsilon j}$ is each locality accessible area "υ" by land cover "j" in ha and P_j is the fuelwood productivity by land cover class "j" in Mg ha^{-1} y^{-1} (dry matter).

The annual fuelwood production variations due to land cover changes between years 1986 and 2000 for each locality accessible area was estimated using the following equation:

$$\mathrm{LCV}_v = \sum_{k=1}^{168} (A_{vk} \times \Delta P_k)/14 \tag{2}$$

where LCV_v is the annual variation in fuelwood production per locality accessible area "v", in Mg y^{-1} (dry matter), due to land cover changes that occurred between years 1986 and 2000 (a 14 year period) in the *Purhepecha* Region; A_{vk} is each locality accessible area "v" by land cover transition "k" in ha (e.g. from pine forests to temporal agriculture); and ΔP_k is the fuelwood productivity change (positive or negative) by land cover transition "k" in Mg ha^{-1} y^{-1} (dry matter). Note that there are a total of 168 land cover potential transitions in which a variation in fuelwood productivity exists. Some of these transitions involve non-fuelwood sources classes (e.g. from pine forests to no vegetation). All land cover categories (15) were included in the transition matrix before discarding those null transitions (e.g. from water bodies to no vegetation) or transitions without change in land cover.

The four parameters used in equations (1) and (2) were estimated by 1) intersecting accessible areas with a land cover map of the study area for the year 2000 (A_{vj}); 2) intersecting accessible areas with a land cover change map of the study area between years 1986 and 2000 (A_{vk}); 3) reviewing the literature in order to assign fuelwood productivities to those land cover classes present in land cover maps from years 1986 and 2000 (P_j) (Table 1); and 4) building a matrix for annual increments and decrement in fuelwood productivities due to land cover changes that occurred between years 1986 and 2000 in the study area (ΔP_k).

3.2.1. *Land cover maps of the study area for years 1986 and 2000*

Land cover maps were obtained through a classification of two satellite images for years 1986 and 2000, from the Landsat Thematic Mapper (TM) and the Enhanced Thematic Mapper plus (ETM+) series respectively. Both images were captured during the dry season (February–April). The interpretation was conducted by a maximum likelihood supervised classification, using the IDRISI32 software. Spectral signatures were created using training site data for 14 vegetation types: 88 ground georeferenced control points were used for 10 land cover classes. For the remaining 4 classes the Mexican National Forest Inventory 2000 was used [34]. A land cover change map (1986–2000) was also obtained.

The classification system was based on the Mexican National Forest Inventory 2000 [34]. Land cover classes were grouped into: 1) rainfed agriculture (seasonally cultivated), 2) irrigated agriculture; 3) secondary forests (degraded pine, pine–oak, and oak forests); 4) fir forests; 5) grasslands; 6) oak forests; 7) pine forests; 8) pine–oak forests; 9) shrublands; 10) fruit trees orchards (avocado orchards and, to a much lesser extent, perennial crops); 11) forest plantations; 12) urban areas; 13) lakes; 14) areas without vegetation; and 15) not determined.

3.2.2. *Fuelwood productivity assignations by land cover classes present in land cover maps*

Fuelwood productivity estimates by land cover class (Table 1) were derived from the study by Ordoñez et al. [25] conducted over the *Purhepecha* Region for the year 2000, in which the carbon content in vegetation, litter and soil was measured by means of field data acquisition, allometric equations and samples collection. Equation (3) shows how the aboveground carbon content of trees and shrubs was converted into an annual woody biomass increment suitable as fuelwood.

$$P_j = \frac{B_j \times 2 \times \mathrm{Ff}_j}{t_j} \tag{3}$$

where B_j is the carbon content in the aboveground portion of trees and shrubs by land cover class "j" in Mg ha^{-1}; 2 is the ratio between carbon and biomass (dry matter); Ff_j is the fuelwood fraction (aboveground biomass suitable as fuelwood) by land cover class "j"; and t_j is the average time needed to reach the aboveground biomass stock in years. Note that $B_j \times 2/t_j$ corresponds to the mean annual increment (MAI) by land cover class.

3.3. *Demand module*

Residential fuelwood demand is a function of 1) the energy needs of households, in terms of cooking, boiling water and space heating; 2) the final use devices (e.g. open fires, cookstoves, etc.); and 3) the portion of the energy needs satisfied by fuelwood. Fuelwood consumption in dry matter was measured in the *Purhepecha* Region by Berrueta et al. [35] for both types of fuelwood users, i.e. exclusive and mixed. Exclusive fuelwood users consume 3.4 ± 0.8 kg day^{-1} cap^{-1} (1.2 ± 0.3 Mg y^{-1} cap^{-1}) and mixed users 2.3 ± 1.1 kg day^{-1} cap^{-1} (0.8 ± 0.4 Mg y^{-1} cap^{-1}). Four poorly correlated indicators related to fuelwood demand, were incorporated into the demand module (fuelwood consumption was incorporated into the integration module):

$$T_l = U_l + M_l \tag{4}$$

where T represents total users per locality "l"; U are exclusive fuelwood users per locality "l" and M represents mixed users per locality "l" (people that use both fuelwood and LPG). U is a variable reported by INEGI census for year 2000 [36], while M was estimated using the following equation:

$$M_l = U_l \times \beta \tag{5}$$

where β is the mixed to exclusive fuelwood users ratio in the *Purhepecha* Region (0.25 ± 0.10).

$$D_v = (U_l + M_l \times 0.68)/A_v \tag{6}$$

where D_v represents fuelwood users' density per locality accessible area "v", in users' ha^{-1}; A_v is each locality accessible area "v", in ha $-$ $A_v = \sum A_j$ (equation (1)). Mixed users were multiplied by 0.68 as per capita fuelwood consumption is 68% of that assumed for exclusive users [35].

$$S_l = F_l/H_l \tag{7}$$

where S_l is the fuelwood saturation per locality "l", as a percentage, F are the number of households that use fuelwood per locality "l", and H are the total number of households per locality "l".

Table 1 – Fuelwood productivity estimates linked to land cover classes.

Land cover class	Aboveground biomass stock in Mg ha^{-1}[a]	Average time needed to reach aboveground biomass stock in years[b]	Mean Annual Increment (MAI) in Mg ha^{-1} y^{-1}[c]	MAI as a percentage of aboveground biomass stock	Fuelwood to aboveground biomass ratio (Ff)[d]	Fuelwood increment in Mg ha^{1} y^{-1}[e]
Agriculture*	15 ± 15	30 ± 8†	0.5 ± 0.5	3%	0.2	0.1 ± 0.1
Secondary forests	145 ± 8	25 ± 6*	7.3 ± 1.9	4%	0.6	3.5 ± 0.9
Fir forests	269 ± 30	45 ± 11‡	9.0 ± 2.4	2%	0.4	2.4 ± 0.7
Grasslands	15 ± 15	30 ± 8†	0.5 ± 0.5	3%	0.2	0.1 ± 0.1
Oak forests	226 ± 22	60 ± 15**	4.5 ± 1.2	2%	0.8	3.0 ± 0.8
Pine forests	201 ± 21	40 ± 10‡	6.7 ± 1.8	3%	0.4	2.0 ± 0.5
Pine–oak forests	183 ± 18	50 ± 13††	4.6 ± 1.2	2%	0.6	2.2 ± 0.6
Shrublands	57 ± 50	40 ± 10‡‡	1.9 ± 1.7	3%	0.8	1.1 ± 1.0

Notes: (*) rainfed or seasonally cultivated agriculture. Land cover classes not considered in the analysis are: irrigated agriculture, fruit trees orchards, forest plantations, urban areas, lakes, areas without vegetation and not determined. Almost no fuelwood is extracted in the region from irrigated agriculture areas, fruit trees orchards and forest plantations for being mostly closed or overseen areas. Other classes simply do not represent significant sources of fuelwood.

a Taken from Ordoñez et al. [25]. The mentioned study does not report trees outside forests (i.e. trees in agriculture and grassland areas), only herbaceous vegetation. A conservative assumption of aboveground biomass stock in agriculture and grassland areas was considered as 1/10 of secondary forests, with a percentage of uncertainty of 100%: from no woody biomass at all to nearly half of shrubland areas. It's worth to mention that in spite of the fact that most authors agree on the important role of non-forest sources in supplying fuelwood for households, the studies providing objective measurement are extremely rare [17]. The values assumed for these two land cover classes should be regarded as a first approximation. For non-anthropic land cover classes error values correspond to standard errors reported in [25].

b (†) Average age of trees outside forests from unpublished own field-based estimates in the *Purhepecha* Region; (*) Pine–oak forests/2; (‡) [26]; (**) [27]; (††) average between pine and oak forests; (‡‡) [28]. A 25% uncertainty was assumed for all land cover classes.

c MAI = (a)/(b).

d Ff corresponds to the aboveground woody biomass suitable as fuelwood. This coefficient integrates two ratios: 1) woody biomass to total biomass and 2) fuelwood to woody biomass [29–33]. For agriculture areas and grasslands, the fraction of aboveground woody biomass suitable as fuelwood was considered equal to the natural mortality (20%). In the study region, trees outside forests are rarely fell down for fuelwood, as they serve to other non-energy purposes such as fences, shadow for the livestock, etc. This is to say, by definition, all fuelwood extracted from agriculture areas and grasslands, as dead wood, are considered renewable.

e Standard error values were propagated using the sum of squares of uncertainties and percentage of uncertainties from input variables, assuming that these are uncorrelated (i.e. covariance terms into the equations are zero) and normally distributed (see Methods and Electronic Annex 4 in the online version of this article).

$$I_l = I_{Nl}/P_{Tl} \tag{8}$$

where I_l is the percentage of people belonging to an ethnic group per locality "l"; I_{Nl} is the number of people over 5 years old that speaks an indigenous language per locality "l" and P_{Tl} is total population per locality "l". This variable is linked to fuelwood use patterns as a proxy measure of the resilience of consumption, as fuelwood use is a cultural characteristic of most ethnic groups in Mexico.

$$C_l = (U_l \times FC) + (M_l \times FCM) \tag{9}$$

where C_l is the fuelwood consumption per locality "l", in Mg y^{-1} (dry matter); FC and FCM are the average per capita fuelwood consumption in the *Purhepecha* Region for exclusive and mixed users in Mg y^{-1} cap^{-1} (dry matter), 1.24 ± 0.06 and 0.84 ± 0.09 respectively. Uncertainty values correspond to the standard error [35].

3.4. *Integration module*

The information gathered in the supply and demand modules was combined to estimate the fuelwood supply/demand balance per locality (B_v):

$$B_v = FWS_v - C_l \tag{10}$$

where B_v is the balance between fuelwood supply and demand per locality accessible area "v", in Mg y^{-1} (dry matter).

3.5. *Identification of fuelwood hot spots*

Three sub-steps were followed in order to identify fuelwood hot spots in the *Purhepecha* Region [16,37]: a) standardization of indicators, b) weight assignment and aggregation procedure, and c) construction of a Fuelwood Priority Index (FPI).

3.5.1. *Standardization of indicators*

Indicators 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 [37,38]. 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 Electronic Annex 3 in the online version of this article.

3.5.2. *Weight assignment and aggregation procedure*

Following Ghilardi et al. [16] and Geneletti [37], three different weight sets were assigned to indicators in order to include different perspectives into the priorization analysis (Table 2). In the first set, equal weights were assigned to all indicators (67% of the overall weight distributed within four demand indicators and 33% 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. The weighted summation technique [39], which consists in adding all weighted standardized scores from all indicators used, was selected.

The weighted summation output per weight set "s" and locality accessible area "υ" is given by the equation:

$$\mathrm{WSO}_{s\upsilon} = \sum_{d=1}^{6} R_{\upsilon d} \times W_{ds} \tag{11}$$

where R is the standardized score per locality accessible area "υ" 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_{sv} vary between 0 and 1.

3.5.3. *Construction of the Fuelwood Priority Index (FPI)*

The final step of the fuelwood hot spots identification analysis was to group all localities in 3 groups of priority according to their WSOs. If each of the 3 WSOs are higher than 0.6, then the locality is ranked as high priority. If each of the 3 WSOs are higher than 0.3 but at least one is lower than 0.6 then the locality is ranked as mid-priority. If at least one WSOs are lower than 0.3 then the locality is ranked as low priority. This procedure gives robustness to the priorization as different weights were assigned to each WSO. Individual indicators' real values can be further analyzed from thematic maps, as for example, fuelwood balance real values.

3.6. *Pressure over natural forests*

The pressure exerted over natural forests by fuelwood extraction was estimated based on the balance equation (equation (10)):

$$\mathrm{PF}_v = B_\upsilon / F_\upsilon \tag{12}$$

where PF_υ is the annual rate of fuelwood extraction from forests on a non-renewable basis per locality accessible area "υ", in Mg ha^{-1} y^{-1} (dry matter) for $B_v < 0$ and $\mathrm{PF}_v = 0$ for $B_v \geq 0$; and F_υ is the forest area per locality accessible area "υ", in ha (all land cover categories in Table 1 account for forest areas, except for agriculture).

As seen in Table 1, fuelwood may come from forest and non-forest areas as well. As mentioned in the table footnotes, the fraction of aboveground woody biomass suitable as fuelwood coming from non-forest areas was assumed equal to the natural mortality (≈20%), assuming that trees are rarely cut for fuelwood as they serve to other non-energy purposes, such as fences, shade for the livestock, etc. This is to say, fuelwood extracted from non-forest areas is considered renewable by definition. So, for unbalance situations, it is assumed that all fuelwood extracted on a non-renewable basis come from forest areas.

Assuming an exponential depletion curve for natural forests due to non-renewable fuelwood extraction, the time needed to deplete half of standing woody biomass stocks suitable as fuelwood in natural forests was estimated based on the following equations:

$$\mathrm{Sto}_{\upsilon t} = \mathrm{Sto}_{\upsilon t0} \times e^{k\upsilon\ t} \tag{13}$$

Where $\mathrm{Sto}_{\upsilon t}$ is fuelwood stock i.e. aboveground woody biomass suitable as fuelwood in forests per locality accessible area "υ" in time "t"; $\mathrm{Sto}_{\upsilon t0}$ is fuelwood stock per locality accessible area "υ" in time 0 (year 2000); and k_υ is the depletion rate per locality accessible area "υ", as a constant proportion of remaining stock.

$$k_{\upsilon t} = \ln\left(\frac{\mathrm{Sto}_{\upsilon t1}}{\mathrm{Sto}_{\upsilon t0}}\right) \tag{14}$$

where $\mathrm{Sto}_{\upsilon t1}$ is fuelwood stock per locality accessible area "υ" in time 1 (year 2001), as the difference between Sto_{vt0} and the amount of fuelwood extracted on a non-renewable basis during the first year (balance).

$$t_{0.5\upsilon} = \frac{\ln\left(\dfrac{\mathrm{Sto}_{\upsilon t0} \times 0.5}{\mathrm{Sto}_{\upsilon t0}}\right)}{k_\upsilon} = \frac{0.69}{k_\upsilon} \tag{15}$$

where $t_{0.5\upsilon}$ is the time needed to deplete half of fuelwood stock per locality accessible area "υ" in years.

Table 2 – Indicators used in the construction of the FPI and weights' assignments.

Indicator	Abbrev.	Equation	Unit	Module of origin	Weight set 1	Weight set 2	Weight set 3
Land cover change (1986–2000)	LCV_υ	(2)	Mg y^{-1}	Supply	0.17	0.30	0.03
FW users	T_l	(4)	Number of users	Demand	0.17	0.03	0.23
FW density	D_υ	(6)	Number of users ha^{-1}	Demand	0.17	0.03	0.23
Saturation (households)	S_l	(7)	%	Demand	0.17	0.03	0.23
Percentage of people belonging to an ethnic group	I_l	(8)	%	Demand	0.17	0.03	0.23
FW balance	B_υ	(10)	Mg y^{-1}	Integration	0.17	0.60	0.06
				Total	1.00	1.00	1.00

Note: row values may not correspond to totals due to round up.

3.7. Estimation of the non-renewable fraction of fuelwood use

The fraction of fuelwood extracted on a non-renewable basis i.e. renewability coefficient, was estimated based on the balance equation (equation (10)):

$$\mathrm{NRFW}_{\upsilon} = B_{\upsilon}/C_{l} \tag{16}$$

where NRFW_{υ} is the fraction of fuelwood consumption extracted on a non-renewable basis per locality accessible area "υ", as a ratio or percentage for $B_{\upsilon} < 0$ and $\mathrm{NRFW}_{\upsilon} = 0$ for $B_{\upsilon} \geq 0$.

3.8. Uncertainty in basic data inputs

Incorporating uncertainties in the analysis permitted to quantify key variables as fuelwood balance and NRFW. See Electronic Annex 4 in the online version of this article for a detailed description of error propagation equations used.

Uncertainties in basic data inputs were incorporated into the analysis for: 1) carbon content estimates in the aboveground portion of trees and shrubs [25] (see notes in Table 1); 2) time needed to reach aboveground biomass stock in years (see notes on Table 1); 3) fuelwood per capita consumption for exclusive and mixed users [35]. Standard error values were calculated from reported statistical parameters: $n = 23$, $M = 3.4$, $\mathrm{SD} = 0.8$, Student's $p < 0.05$ for exclusive users; and $n = 20$, $M = 2.3$, $\mathrm{SD} = 1.1$, Student's $p < 0.05$ for mixed users; and 4) mixed to exclusive fuelwood users ratio in the *Purhepecha* Region (0.25 ± 0.10). All variables were assumed independent i.e. covariance terms into error propagation equations are zero, and normally distributed.

Please refer to Electronic Annex 2 in the online version of this article for a simplified workflow diagram of the overall methodology.

4. Results and discussion

4.1. Selection of the basic spatial unit (BSU) of analysis by means of accessible areas and aggregation of BSUs into Neighbor Localities Clusters (NLCs)

As accessible areas i.e. BSUs, do not correspond to administrative divisions, overlapping occurred with adjacent or neighbor localities. As explained above, calculation of indicators needs that BSUs do not overlap in order to avoid double counting. Overlapping accessible areas were then aggregated, and all parameters and indicators associated to them (e.g. fuelwood supplies, fuelwood users, saturation, etc.). The new accessible areas were named as Neighbor Localities Clusters (NLCs). Fig. 2 shows an example of an NLC in the northern county of *Chilchota* considering both: walking fuelwood gatherers and fuelwood gatherers using motorized vehicles. When considering walking fuelwood gatherers, the 90 BSUs – each one corresponding to one locality – were merged into 56 non-overlapped localities and NLCs (Fig. 3). Accessible areas extent increase when considering fuelwood gatherers using motorized vehicles, and so occurrences of overlapping areas. In this case, accessible areas were aggregated, in order to maximize the number of NLCs and minimize overlapping areas. The 90 BSUs – each one corresponding to one locality – were merged into 13 NLCs with minimum overlapping areas (Fig. 4).

Two key differences exist between BSUs from the national and sub-county assessments i.e. counties and accessible areas around localities, besides from their spatial scale and detail: 1) counties do not overlap between each other while accessible areas do, and 2) counties areas are fixed while accessible areas vary with different assumptions; in our study, the means of transportation of gatherers. When estimating accessible areas which are defined as those areas from which each locality extract their fuelwood, other factors may be added as well, as for example, other less preferred species as spatial attraction variables, new time limits for walking fuelwood gatherers or legal restrictions from third administrative divisions (corresponding in Mexico to communal, private and federal properties). However, not always all the desired information is available. So, although modeling accessible areas at a sub-county level of analysis is based on field data acquisition and available georeferenced data (average time spent for collecting fuelwood, displacement velocities of gatherers, preferred species distribution, among others), they are indeed a simplified version of reality and may vary between localities of the same region. As mentioned above, the analysis conducted was meant to provide relative/qualitative values rather than absolute/quantitative data, except for the fraction of fuelwood extracted in a non-renewable basis (NRFW). In other words, if basic assumptions for determining accessible areas vary to some extent, the spatial patterns of localities and NLCs priorization should not. Moreover, we were very conservative concerning uncertainties in basic data assumptions, so, rather small changes in accessible areas will be diluted within the propagated overall error of model results.

4.2. Fuelwood hot spots in the Purhepecha Region

Following a similar approach and index calculation as the one used in the national assessment [16], the newly identified BSUs were assessed by means of each indicator and ranked following the Fuelwood Priority Index (FPI). Figs. 3 and 4 show priorities among localities and NLCs based on the Fuelwood Priority Index (FPI) for walking fuelwood gatherers alone: 20 high priority localities grouped in 8 NLCs; and including fuelwood gatherers using motorized vehicles: 11 high priority localities grouped in 2 NLCs. As mentioned in the Introduction, fuelwood hot spots or high priority localities were defined as areas where: (a) insufficient fuelwood resources could be negatively affecting a major number of residential fuelwood users and (b) fuelwood extraction for residential use could be exerting pressure on natural woody areas.

From Figs. 3 and 4 it can be seen that high priority localities and NLCs from this study are mainly distributed over high priority counties previously identified in the WISDOM national assessment. This result confirms the inter-scale congruence between the WISDOM national assessment and this study, although statistical spatial correlation should be further conducted.

Considering walking fuelwood gatherers (Fig. 3), it can be seen that contrasting situations co-exist in a single county, as compared with the WISDOM national assessment that

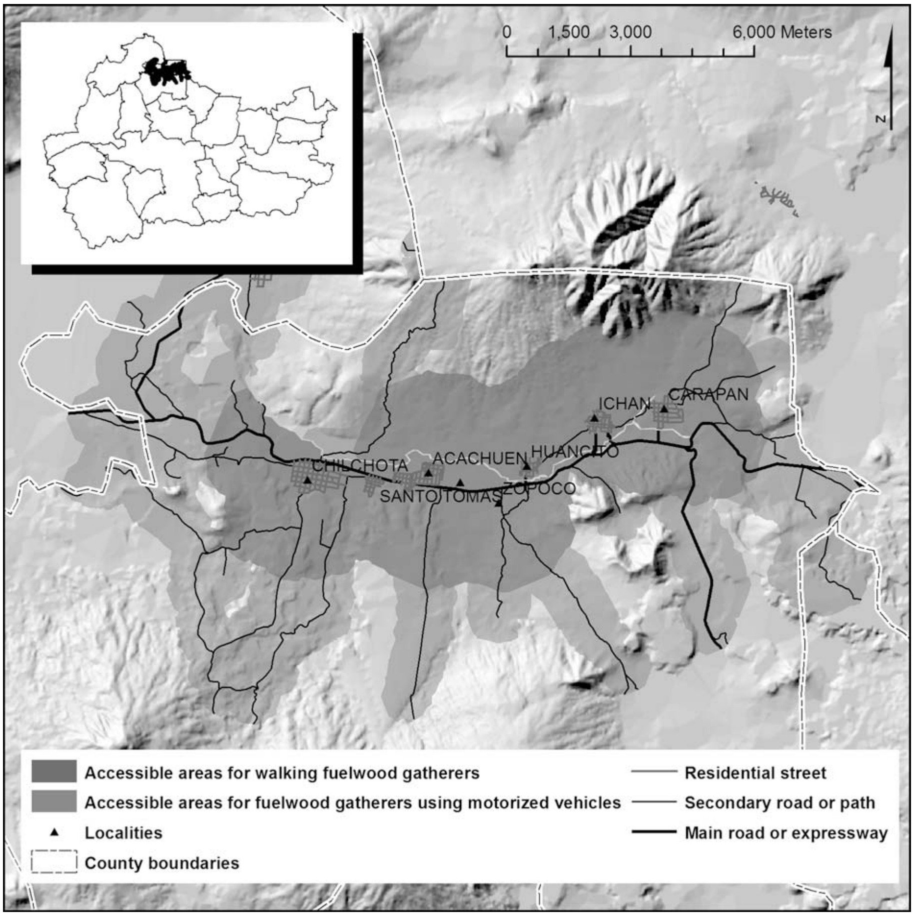

Fig. 2 – Accessible area for a Neighbor Localities Cluster (NLC) considering both: walking fuelwood gatherers and fuelwood gatherers using motorized vehicles.

categorized each county with only one, spatially indivisible index of priority. For example, in the counties of Chilchota (C), Nahuatzen (E) and Uruapan (R), low and high priority localities and NLCs are present. What the WISDOM national assessment considered as high and mid-high priority counties, are in fact a blend of local situations unevenly distributed. Although these situations were highly expected, they could not be consistently analyzed before the present study.

When including fuelwood gatherers using motorized vehicles the number of NLCs (13) is lower than counties in the region (19), so, what further information does this figure show over the WISDOM national assessment results? First, the analysis was based on basic data obtained directly from the region, so it's expected to be more accurate than the national assessment. Second, this figure should be read along with Fig. 3: if localities and NLCs considering only walking fuelwood gatherers were ranked as low priority, it's improbable that including fuelwood gatherers using motorized vehicles will reverse this situation. On the contrary, if high priority localities and NLCs continue to be so after including fuelwood gatherers using motorized vehicles, it means that the situation is critical, as no matter which means of transportation do people have, fuelwood shortages and environmental negative impacts are probably present. These kind of situations favors two broad alternatives depending on the mean income of affected populations: people should go further for fuelwood or buy it from local markets. It's expected that as people need to walk or travel farther to collect fuelwood, legal boundaries may have more influence on accessibility restrictions, favoring local markets over collection for self-consumption. It is worth to remark that fuelwood gathering in the *Purhepecha* Region is seldom done with motorized vehicles. Following the above mentioned rationale, results from expanded accessible areas should be regarded as a tool for scenario building, rather than a description of the existing situation.

Finally, as with the WISDOM national analysis, priorization results should be used at the regional scale to identify patterns of distribution of priority situations and rank, in a relative way, those selected BSUs. Quantitative values aimed at estimating how much critical a single locality or NLC might be, should be considered along with their confidence intervals.

4.3. *Pressure over natural forests*

Fig. 5 shows the annual rate of fuelwood extraction from forests on a non-renewable basis per locality or NLC, considering walking fuelwood gatherers. Accessible forests represent 15% (62 000 ha) of the total forest area (400 000 ha – shaded dark grey), while forests where fuelwood is extracted on

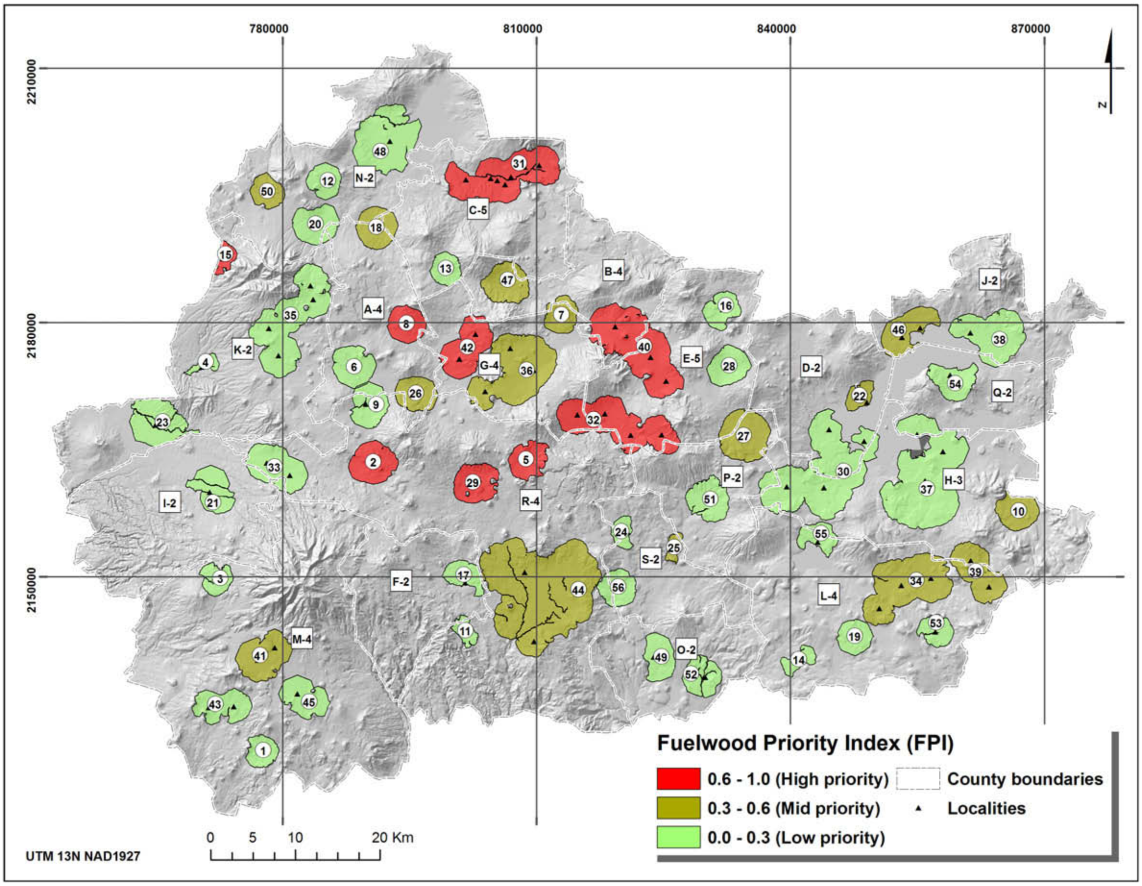

Fig. 3 – Priorization of single localities and Neighbor Localities Clusters (NLCs) based on the Fuelwood Priority Index (FPI) for walking fuelwood gatherers. Notes: Squared letters and numbers correspond to the county name and the FPI from the national priorization respectively [16]. (A) *Charapan*; (B) *Cherán*; (C) *Chilchota*; (D) *Erongaricuaro*; (E) *Nahuatzen*; (F) *San Juan Nuevo Parangaricutiro*; (G) *Paracho*; (H) *Pátzcuaro*; (I) *Periban*; (J) *Quiroga*; (K) *Los Reyes*; (L) *Salvador Escalante*; (M) *Tancítaro*; (N) *Tangancicuaro*; (O) *Taretan*; (P) *Tingambato*; (Q) *Tzintzuntzan*; (R) *Uruapan*; (S) *Ziracuaretiro*. 5 = High priority; 4 = mid-high priority; 3 = mid-priority; 2 = mid-low priority; 1 = low priority. Circled numbers correspond to single localities and NLCs: (1) *Agua Zarca*; (2) *Angahuan*; (3) *Apo*; (4) *Atapan*; (5) *Capácuaro*; (6) *Charapan*; (7) *Cheran Atzicuirin* (*Cheránastico*); (8) *Cocucho*; (9) *Corupo*; (10) *Cuanajo*; (11) *Cutzato* (*Cuisato*); (12) *General Damaso Cárdenas* (*Páramo*); (13) *Huecato*; (14) *Ístaro*; (15) *J. Jesus Diaz Tzirio*; (16) *La Mojonera*; (17) *Nuevo San Juan Parangaricutiro*; (18) *Ocumicho*; (19) *Paramuén*; (20) *Patamban* (*Patambam*); (21) *Peribán de Ramos*; (22) *Puácuaro*; (23) *Los Reyes de Salgado*; (24) *San Andrés Coru*; (25) *San Ángel Zurumucapio*; (26) *San Felipe de los Herreros* (*San Felipe*); (27) *San Francisco Pichátaro* (*Pichátaro*); (28) *San Isidro2*; (29) *San Lorenzo*; (30) *NLC_Ajuno*; (31) *NLC_Cañada*; (32) *NLC_Comachuén*; (33) *NLC_Nuevo Zirosto*; (34) *NLC_Opopeo*; (35) *NLC_Pamatácuaro*; (36) *NLC_Paracho*; (37) *NLC_Pátzcuaro*; (38) *NLC_Quiroga*; (39) *NLC_Santa Juana*; (40) *NLC_Sevina*; (41) *NLC_Tancítaro*; (42) *NLC_Urapicho*; (43) *NLC_Uringuitiro*; (44) *NLC_Uruapan*; (45) *NLC_Zirimbo*; (46) *NLC_Ziróndaro*; (47) *Tanaco*; (48) *Tangancicuaro de Arista*; (49) *Taretan*; (50) *Tenguecho*; (51) *Tingambato*; (52) *Tomendán*; (53) *Turirán*; (54) *Tzintzuntzan*; (55) *Zirahuén*; (56) *Zirimicuaro*.

a non-renewable basis i.e. unbalanced situations highlighted red and yellow, represent 52% (32 000 ha) of total accessible forests and 8% of the total forest area.

Oak forests cover 9600 ha in the region. About 1000 ha exist within high pressure areas. As oaks are preferred for fuelwood, it would be expected that identified patches are prone to degradation due to fuelwood extraction, unless some kind of coppice regrowth management or any other alternative is conceived by the local population. Oak patches in low demanding areas of fuelwood for self-consumption are not free from degradation as they are a potential source of income as a local trade good, particularly if they are surrounded by deficitary localities.

Labels on Fig. 5 show the expected time needed to deplete half of standing woody biomass stocks suitable as fuelwood in natural forests, assuming an exponential depletion curve.

When considering expanded accessible areas by including fuelwood gatherers using motorized vehicles (Fig. 6), pressure on forests diminishes significantly as more area is available for extracting the same amount of fuelwood. However, as mentioned in Section 4.2, fuelwood is seldom extracted with the help of motorized vehicles. So, it is expected that under a non-renewability scenario, people will go farther for fuelwood to the extent that the nearer enough supplying areas are depleted first.

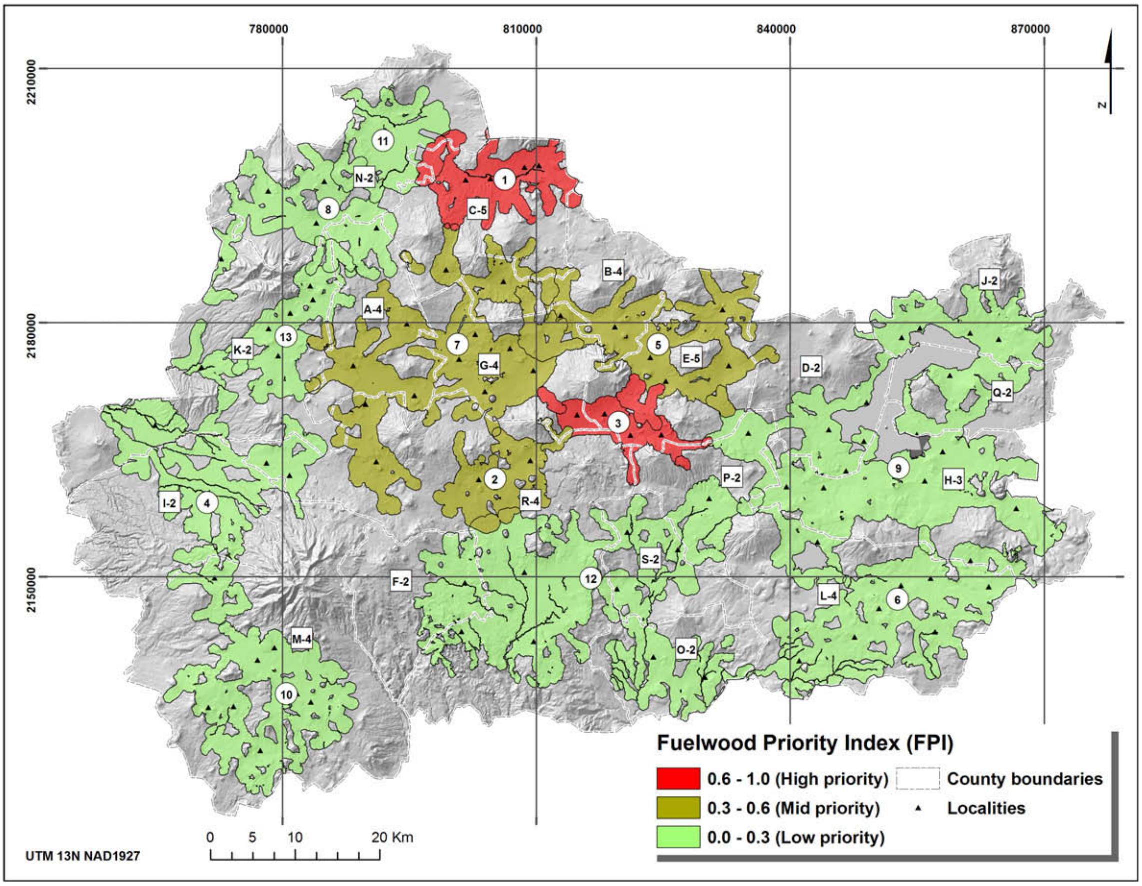

Fig. 4 – Priorization of single localities and Neighbor Localities Clusters (NLCs) based on the Fuelwood Priority Index (FPI) for both: walking fuelwood gatherers and fuelwood gatherers using motorized vehicles. Notes: Squared letters and numbers correspond to the county name and the FPI from the national priorization respectively [16]. (A) *Charapan*; (B) *Cherán*; (C) *Chilchota*; (D) *Erongaricuaro*; (E) *Nahuatzen*; (F) *San Juan Nuevo Parangaricutiro*; (G) *Paracho*; (H) *Pátzcuaro*; (I) *Periban*; (J) *Quiroga*; (K) *Los Reyes*; (L) *Salvador Escalante*; (M) *Tancítaro*; (N) *Tangancicuaro*; (O) *Taretan*; (P) *Tingambato*; (Q) *Tzintzuntzan*; (R) *Uruapan*; (S) *Ziracuaretiro*. 5 = High priority; 4 = mid-high priority; 3 = mid-priority; 2 = mid-low priority; 1 = low priority. Circled numbers correspond to NLCs: (1) *NLC_Cañada*; (2) *NLC_Capácuaro*; (3) *NLC_Comachuén*; (4) *NLC_Los Reyes*; (5) NLC_Nahuatzen; (6) *NLC_Opopeo*; (7) *NLC_Paracho*; (8) *NLC_Patamban*; (9) *NLC_Pátzcuaro*; (10) *NLC_Tancítaro*; (11) *NLC_Tangancicuaro*; (12) *NLC_Uurapan*; (13) *NLC_Zuicuicho*.

Oak forest patches lying within areas only accessible to fuelwood gatherers using motorized vehicles (arrows in Fig. 6) are prone to degradation as this type of gatherers are often fuelwood sellers looking for oaks, using chainsaws and cutting down as many trees as the vehicle can carry out.

Deforestation resulting from woodfuel extraction has been a contested issue. For example, in the 1970s and 80s, demand for subsistence woodfuel was thought to be a primary driver of deforestation, but more recent analyses, have shown that these impacts are highly contingent on both social and environmental factors. Our results show that forest areas prone to degradation by fuelwood extraction can be indeed identified using spatially explicit approaches, even though estimated values of pressure over forests and expected depletion rates are associated to wide uncertainty ranges. Ground truthing efforts should be conducted over those identified areas, by means of updated satellite images and field data acquisition, among others.

4.4. *Non-renewable fuelwood fraction (NRFW)*

The non-renewable fuelwood fraction (NRFW) (equation (16)) shows the proportion this amount represents with respect to fuelwood consumption. Balance and NRFW estimates are key indicators for deriving baselines in business as usual (BAU) scenarios for carbon offset projects involving non-renewable biomass (NRB) estimates. Net CO_2 emissions from non-renewable fuelwood consumption can then be added to products of incomplete combustion (PIC) diverted from wood burning in traditional household stoves, and so have an estimate of CO_2eq emissions in the baseline. Currently, renewability estimates are taken either from aggregated areas and used in every locality included in the project, or else are derived from site-specific analyses and then extrapolated to a whole region [40].

By comparing both the balance and NRFW estimates for the whole *Purhepecha* Region and for the top 10 scoring localities and NLCs in Table 3, we argue that both approaches are equally wrong as the quantification of renewability aimed at

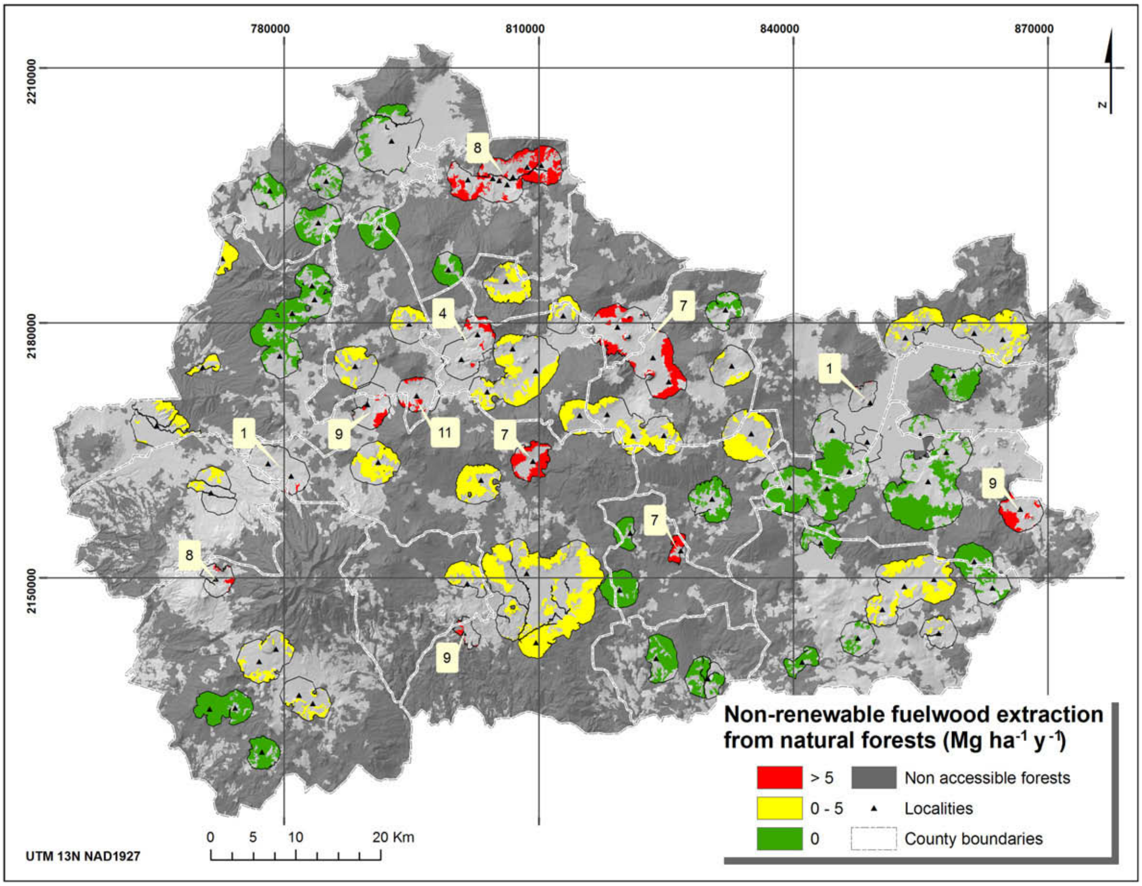

Fig. 5 – Pressure over natural forests due to fuelwood extraction on a non-renewable basis from accessible areas considering walking fuelwood gatherers. Notes: Highlighted red, yellow and green areas within accessible areas correspond to accessible forests. Dark-grey areas correspond to non-accessible forests. Labels show the expected time in years for depletion of half the fuelwood stock available from forest areas.

locality-based carbon offset projects must be conducted on a locality by locality basis, if misleading estimates are to be avoided.

The aggregated balance and NRFW estimates for the region varied widely when considering localities with at least 100 and 20 households using fuelwood, respectively. This is because, as more localities are included in the analysis, more area will be supplying fuelwood, although demand will not increase in the same proportion given the low number of households using fuelwood in these localities. This result clearly exemplifies how deficitary localized situations may exist within a region that overall aggregated estimates render positive (for the case of balance) or fully renewable (for the case of NRFW). Based on the *Purpecha* Region aggregated values shown in Table 3, all localities should be assigned a 25 ± 16% NRFW; clearly a false or misleading value when considering individual estimates of selected localities that extract their fuelwood on a non-renewable basis (with NRFW values ranging from 0 to 96% (for the case of *NLC_Nuevo Zirosto*, see Fig. 3.). If these last localities were selected for carbon offset projects a large underestimation of NRFW will result using the current methods. Note moreover from Fig. 5 how wide variations in estimates occur even among adjacent or neighbor localities. For a detailed description of a proposed integrated methodology for including locality-based estimates and renewability into carbon offset projects using efficient cookstoves please refer to Johnson et al. [40]. For carbon offset projects applying to the Clean Development Mechanism (CDM) of the Kyoto Protocol, other conditions must be met along with assuring that fuelwood extraction is not outpacing woody biomass increments [41].

4.5. *Aggregated individual indicators' values as compared with the national WISDOM analysis*

Although the outcomes of the present analysis allow identifying localized situations at the sub-county level, this is to say inside a single county, comparing mean values by county with those from the national assessment [16], give useful information about how much the values of key indicators varied between both analyses. As mentioned in the Introduction, the same set of indicators used in the national assessment was selected for this study. Yet: 1) variations in fuelwood production due to land cover changes could not be compared as two time periods were used: 1993–2000 for the national assessment, and 1986–2000 for the present study; 2)

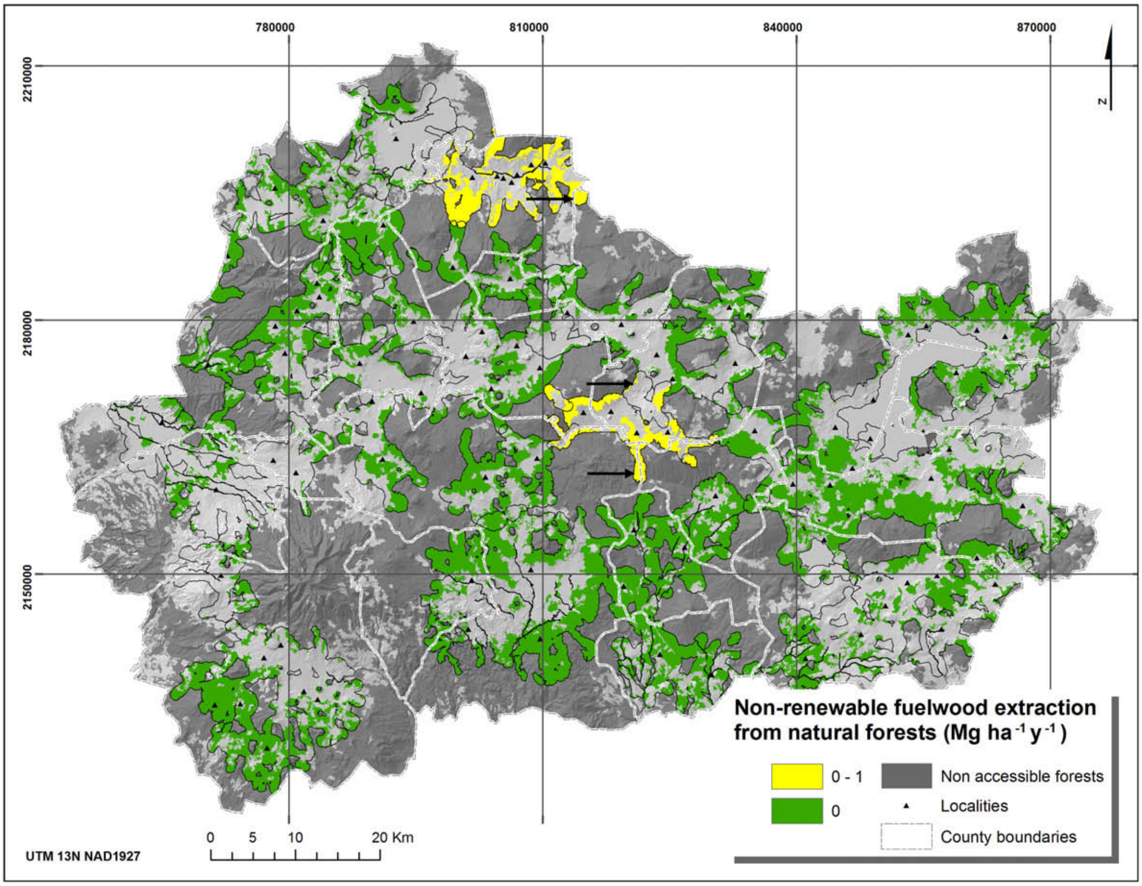

Fig. 6 – Pressure over natural forests due to fuelwood extraction on a non-renewable basis from accessible areas considering both: walking fuelwood gatherers and fuelwood gatherers using motorized vehicles. Notes: Highlighted yellow and green areas within accessible areas correspond to accessible forests. Dark-grey areas correspond to non-accessible forests. (1) *NLC_Cañada* = 0.74 Mg ha^{-1} y^{-1} and (3) *NLC_Comachuén* = 0.90 Mg ha^{-1} y^{-1}. Arrows point at remanent oak forests' patches only accessible to fuelwood gatherers using motorized vehicles. Expected time for depletion of half the fuelwood stock available from forest areas exceed 70 years in both NLCs.

in the national assessment all localities with at least 20 households relying on fuelwood were included; the present analysis was run again including this new set of localities; 3) in order to obtain aggregated data at the county level and avoid double counting due to overlapping accessible areas, all localities inside a single county were merged into a unique starting points set; and finally 4) data for the 19 counties conforming the *Purhepecha* Region was obtained from the original national WISDOM geodatabase; although these results were not reported separately in Ghilardi et al. [16]. Although the locality-based census was used in the national assessment for calculating fuelwood users per county, national-based results cannot be disaggregated by locality, as all localities in each county have the same average value for each indicator. This is to say, results from the national assessment are spatially indivisible beyond the county level, namely the BSU.

Table 4 shows key indicators aggregated for the *Purhepecha* Region as compared with the WISDOM national assessment [16]. Generally, the present analysis rendered more accurate mean estimates, as seen by narrower confidence intervals. Almost all of the region's area is considered accessible by the national assessment, by assuming wide linear buffers around localities and at each side of main roads. Incorporating topographical and land cover variables reduced accessible areas in about 50%. Fuelwood supply decreased between the national and sub-county assessments as this indicator is directly dependent of accessible areas. However, variations in this indicator are also due to the fact that fuelwood productivity assumptions were different between both assessments. Although fuelwood users' number were the same, fuelwood consumption increased for this study as per capita assumptions were higher than those used in the national estimates for the same area, which were based on broad eco-climatic zones (averaging 2.5 ± 0.5 kg per capita per day for exclusive users, instead of 3.4 ± 0.8 for the present study). Fuelwood balance decreased between the national assessment and this study, because of lower fuelwood supplies and higher consumption estimates. It is important to highlight that in the national assessment, net CO_2 emissions from non-renewable fuelwood use by the residential sector were shown

Table 3 – Top 10 localities and NLCs with the highest values for negative balances and NRFW.

Classification number (Fig. 3)	Locality or NLC name	Balance (B) eq. (10), in Gg y^{-1}	Confidence interval
31	*NLC_Cañada*[a]	−16.2 ± 2.5	−21.0 to −11.3
40	*NLC_Sevina*[a]	−15.1 ± 1.7	−18.5 to −11.7
32	*NLC_Comachuén*[a]	−9.1 ± 1.7	−12.5 to −5.8
5	*Capácuaro*[a]	−7.2 ± 0.8	−8.7 to −5.6
34	*NLC_Opopeo*	−7.1 ± 1.5	−9.9 to −4.2
42	*NLC_Urapicho*[a]	−5.4 ± 0.6	−6.5 to −4.3
10	*Cuanajo*	−3.5 ± 0.5	−4.5 to −2.5
2	*Angahuan*[a]	−2.8 ± 0.7	−4.2 to −1.3
25	*San Ángel Zurumucapio*	−2.7 ± 0.3	−3.4 to −2.1
33	*NLC_Nuevo Zirosto*	−2.2 ± 0.2	−2.6 to −1.9
Regions' totals	*Localities ($n = 56$) with at least 100 households using fuelwood, and rendering only negative balance values (58% of total fuelwood consumption)*	−93 ± 24	−139 to −46
	All localities ($n = 90$) with at least 100 households using fuelwood rendering negative and positive balance values (76% of total fuelwood consumption)	−62 ± 39	−139 to 14
	All localities ($n = 298$) with at least 20 households using fuelwood rendering negative and positive balance values (95% of total fuelwood consumption)	64 ± 72	−78 to 206
Classification number (Fig. 3)	Locality or NLC name	NRFW eq. (16), in percentage	Confidence interval
33	*NLC_Nuevo Zirosto*	96 ± 10	76–100
22	*Puácuaro*	93 ± 11	71–100
42	*NLC_Urapicho*[a]	83 ± 10	63–100
3	*Apo*	77 ± 10	57–97
5	*Capácuaro*[a]	75 ± 10	55–95
40	*NLC_Sevina*[a]	75 ± 10	55–95
25	*San Ángel Zurumucapio*	74 ± 10	54–94
31	*NLC_Cañada*[a]	69 ± 12	45–93
10	*Cuanajo*	67 ± 11	45–89
26	*San Felipe de los Herreros (San Felipe)*	64 ± 12	40–88
Regions' totals	*All localities ($n = 90$) with at least 100 households using fuelwood (76% of total fuelwood consumption)*	25 ± 16	0–56
	All localities ($n = 298$) with at least 20 households using fuelwood (95% of total fuelwood consumption)	Renewable	

Notes: Uncertainty values correspond to propagated standard errors. Confidence intervals assuming an alpha significance level of 0.05 (z-value = 1.96).

NRFW = non-renewable fuelwood. NLC = Localities Cluster.

[a] Ranked as high priority by the FPI (see Section 4.2).

disaggregated by county, and from this information, a national estimate of GHG emissions was drawn. As seen by results from Table 4, the *Purhepecha* Region resulted in a positive balance i.e. no net emissions, although present results show that deficitary situations exist within the region. We strongly believe that when dealing with national estimates of the proportion of non-renewable harvested fuelwood, a key value for GHG emissions inventories, basic assumptions must be carefully evaluated in order to be the most conservative as possible, favoring false positive (type I) errors. While, as mentioned above, when the proportion of non-renewable harvested fuelwood is aimed for carbon offset projects (e.g. CDM), a locality by locality analysis should be conducted.

Key questions arise when comparing both analyses: is it worth the effort – in terms of financial resources and GIS analysis – to go further into a sub-county scale of analysis? What new information for implementing bioenergy projects does the sub-county analysis give compared with the previous assessments disaggregated by county? The answer to these questions depends on two factors: 1) the number and spatial distribution of localities within counties or any BSUs used at the national scale analysis. If on average, BSUs are ''saturated'' with localities, and these are close enough to forbid individual accessible areas identification, then the sub-county analysis will improve the accuracy and precision of outcomes, without adding substantial information in terms of fuelwood supply/demand spatial patterns. On the contrary, if localities within BSUs are unevenly distributed and the identification of individual accessible areas is possible, then a sub-county analysis will highlight differences between localities within a single BSU, as shown in the present study; 2) the basic underlying question behind the analysis. For example, in order to maximize its effectiveness and reduce costs, intervention projects aimed at improving the fuelwood situation in critical areas, rather than being implemented on all localities within selected fuelwood hot spots identified at the national level, could be much more precisely identified using the WISDOM sub-county analysis.

Table 4 – Aggregated indicators for the *Purhepecha* Region as compared with the previous WISDOM national assessment.

Indicator	National assessment		This study	
	Mean	Confidence interval[a]	Mean	Confidence interval[b]
Accessible area in thousand of hectares	653	609 to 653	279	
Fuelwood supply (FWS) in Gg y^{-1}	901	196 to 1583	377	242 to 511
Fuelwood users (T) in thousand of users	270	216 to 324	270	228 to 312
Fuelwood consumption (C) in Gg y^{-1}	253	169 to 352	314	267 to 359
Fuelwood balance (B) in Gg y^{-1}	647	−156 to 1415	64	−78 to 206

Notes: All localities ($n = 298$) with at least 20 households using fuelwood were analyzed in both approaches. Selected localities account for 95% of total fuelwood consumption in the *Purhepecha* Region.

a Confidence intervals were set based on minimum and maximum input 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 [16].

b Confidence intervals assuming an alpha significance level of 0.05 (z-value = 1.96), and calculated from propagating standard errors associated to input variables. See Electronic Annex 4 for details. Uncertainties in basic data inputs were incorporated into the analysis for: 1) aboveground biomass stock; 2) time needed to reach aboveground biomass stock; 3) fuelwood per capita consumption for exclusive and mixed users; and 4) mixed to exclusive fuelwood users ratio in the study area. All variables were assumed independent i.e. covariance terms into the equations are zero, and normally distributed (see Section 3.8).

5. Conclusions and future research directions

In a previous analysis at the national level, 304 high priority counties (HPCs) in terms of fuelwood use, spatially aggregated pattern into 16 clusters or county-based fuelwood hot spots were identified in Mexico [16]. In this paper, we developed a regional WISDOM approach over one of these 16 fuelwood hot spots, identifying 20 localities, out of a total of 90, as high priority or critical in terms of the same six indicators used for the national assessment. The 20 localities resulted grouped in 8 clusters or locality-based fuelwood hot spots distributed between 6 adjacent counties, out of 19 in the study area.

We argued that this approach is innovative because, starting from a national perspective, it allows identifying the most critical local situations with respect to fuelwood use, while using available information, few financial and human resources and a straight forward methodology. In other words, the approach helps focus resources and attention on those most critical local situations, bridging the gap between national aggregated studies and local site specific surveys.

WISDOM national assessments (aimed at identifying county-based fuelwood hot spots), are a useful tool for incorporating traditionally used woodfuels into the national energy planning agenda and to start focusing actions on the most critical regions or counties. On the other hand, WISDOM sub-national assessments (aimed at identifying locality-based fuelwood hot spots), are a useful tool for designing and implementing concrete actions or intervention projects derived from the national agenda.

It’s worth to notice that local trade can modify the balance and renewability estimates for neighbor contrasting localities in terms of fuelwood surplus and deficit, assuming surpluses’ localities may sell their extra fuelwood to deficit ones. Although local trade between localities is not well established yet in the region, it deserves further attention and understanding in order to model it consistently. In this sense, trade offs may be expected to arise from the implementation of projects within those most critical localities inside a fuelwood hot spot; for example, improving the access to fuelwood resources and/or the end use efficiency of fuelwood consumption could negatively impact those other localities which sell their surpluses of fuelwood; or social conflicts may arise between NGOs applying bioenergy projects and local companies providing LPG for mixed users. Integrative and participatory-based surveys, such as the MESMIS framework [42], should be applied before designing and implementing concrete actions over targeted localities.

Finally, given the set of indicators considered in both analyses, there are no theoretical restrictions for conducting an analysis at the sub-county level covering the entire national territory. However, we argue that the benefit-cost ratio is by far more favorable when following the proposed multi-scale approach than conducting such a hypothetical detailed analysis, which will require hardly available inputs and an impressive computing capacity.

Acknowledgements

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biombioe.2009.02.005

REFERENCES

[1] IEA. Energy for cooking in developing countries. In: OECD/IEA, editor. World energy outlook 2006. Paris: International Energy Agency (IEA); 2006. p. 419–45.

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

[3] Righelato R, Spracklen DV. Carbon Mitigation by biofuels or by saving and restoring forests? Science 2007;317:902.

[4] Tilman D, Hill J, Lehman C. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 2006;314:1598.

[5] Stupak I, Asikainen A, Jonsell M, Karltun E, Lunnan A, Mizaraite D, et al. Sustainable utilisation of forest biomass for energy – possibilities and problems: policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. Biomass and Bioenergy 2007;31(10):666–84.

[6] Kirschbaum MUF. To sink or burn? A discussion of the potential contributions of forests to greenhouse gas balances through storing carbon or providing biofuels. Biomass and Bioenergy 2003;24:297–310.

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

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

[9] Arnold M, Köhlin G, Persson R, Shepherd G. Fuelwood revisited: what has changed in the last decade? Occasional paper N°39. Bogor Barat, Indonesia: Center for International Forestry Research (CIFOR). Available on the Internet: http://www.cifor.cgiar.org/publications/pdf_files/OccPapers/OP-39.pdf; 2003 [last visited on November 2008].

[10] Rüdger N. Dynamics and sustainable use of species-rich moist forests. A process-based modeling approach. Thesis. Center for Environmental research-UFZ, Helmholtz; 2006.

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

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

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

[14] 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.

[15] Masera O, Drigo R, Trossero MÁ. 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: Food and Agriculture Organization (FAO) of the United Nations (UN). Available on the Internet: http://www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/005/y4719e/y4719e00.htm; 2003 [last visited on November 2008].

[16] Ghilardi A, Guerrero G, Masera O. Spatial analysis of residential fuelwood supply and demand patterns in Mexico using the WISDOM approach. Biomass and Bioenergy 2007;31:475–91.

[17] 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: Food and Agriculture Organization (FAO) of the United Nations (UN). Available on the Internet: http://www.fao.org/docrep/009/j8227e/j8227e00.HTM; 2007 [last visited on November 2008].

[18] 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: Food and Agriculture Organization (FAO) of the United Nations (UN). Available on the Internet: http://www.fao.org/nr/geo/abst/geo_071101_en.htm; 2007 [last visited on November 2008].

[19] Ghilardi A. Estimación espacial de la oferta de madera para energía en Brasil. São Paulo: Fundação Memorial da América Latina; 2007.

[20] Drigo R. WISDOM Senegal: analysis of woodfuel production–consumption patterns in Senegal. Consultancy report, FAO Wood Energy Programme. Rome: Food and Agriculture Organization (FAO) of the United Nations (UN); 2004.

[21] Drigo R. WISDOM Slovenia: analysis of spatial woodfuel production – consumption patterns in Slovenia. ‘‘Supply and utilization of bioenergy to promote sustainable forest management’’ TCP/SVN/2901. Rome: Food and Agriculture Organization (FAO) of the United Nations (UN); 2004.

[22] CDM. Executive Board approved small scale methodology: energy efficiency measures in thermal applications of non-renewable biomass. Reference number AMS-II.G. Available on the Internet: http://cdm.unfccc.int/UserManagement/FileStorage/CDM_AMSUT12SPEL6M69U60GBKV3OOYZERRHLK; 2008 [last visited on January 2009].

[23] 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.

[24] Pokharel S, Kharal D, Ozdamar L. Spatial model for wood energy analysis. International Journal of Global Energy Issues 2004;21(1/2):79–98.

[25] Ordoñez JAB, De Jong BHJ, García-Oliva F, Aviña FL, Ventura J, Guerrero G, et al. Carbon content in vegetation, litter, and soil under ten different land-use and land-cover classes in the central Highlands of Michoacan, Mexico. Forest Ecology and Management 2008;255(7):2074–84.

[26] NFI, National Forestry Inventory. Memoria Nacional de la Subsecretaría Forestal y de Fauna Silvestre. Mexico City: Secretaría de Agricultura y Recursos Hidráulicos; 1994.

[27] Bonfil C. Regeneration and population dynamics of quercus rugosa at the Ajusco Volcano, Mexico. In: Kappelle M, editor. Ecology and conservation of neotropical montane oak forests. Berlin: Springer; 2006. p. 155–63.

[28] 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.

[29] Brown S. Estimating biomass and biomass change of tropical forests: a primer. FAO forestry paper 134. Rome, Italy: FAO; 1997.

[30] Brown S, Gillespie AJR, Lugo AE. Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science 1989;35:881–902.

[31] Brown S, Lugo AE. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. Biotropica 1982;14:161–87.

[32] Cannell MGR. Woody biomass of forests Stands. Forest Ecology and Management 1984;8:299–312.

[33] Cannell MGR. Dry matter partitioning in tree crops. In: Cannell MGR, Jackson JE, editors. Attributes of plant trees as crop plants. Huntingdown, United Kingdom: Institute of Terrestrial Ecology; 1985. p. 160–93.

[34] Palacio JL, Bocco G, Velázquez A, Mas JF, Takaki-Takaki F, Victoria A, et al. La Condición Actual de los Recursos Forestales en México: Resultados del Inventario Forestal Nacional. Investigaciones Geográficas – Boletín del Instituto de Geografía (UNAM) 2000;43(5):183–203.

[35] Berrueta VM, Edwards R, Masera O. Energy performance of wood-burning cookstoves in Michoacan, Mexico. Renewable Energy 2007;33(5):859–70.

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

[37] Geneletti D. A GIS-based decision support system to identify nature conservation priorities in an alpine valley. Land Use Policy 2004;21:149–60.

[38] Beinat E. Value functions for environmental management. Dordrecht: Kluwer; 1997.

[39] Janssen R. On the multi-criteria analysis in environmental impact assessment. Journal of Multi-Criteria Decision Analysis 2001;10:101–9.

[40] Johnson MA, Edwards R, Ghilardi A, Berrueta V, Gillen D, Alatorre C, et al. Quantification of carbon savings from improved biomass cookstove projects. Environmental Science and Technology, in press.

[41] CDM. Executive Board report annex 18: definition of renewable biomass. Bonn: United Nations Framework Convention for Climate Change (UNFCCC). Available on the Internet: http://cdm.unfccc.int/EB/023/eb23_repan18.pdf; 2006 [last visited on November 2008].

[42] Masera O, Astier M, López-Ridaura S. Sustentabilidad y el manejo de recursos naturales: El marco de evaluación MESMIS. México DF: Mundi-Prensa México; 2000.