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Centro de Investigaciones en Ecosistemas
(CIEco)

ANÁLISIS MULTI-ESCALAR DE LOS PATRONES ESPACIALES DE OFERTA Y DEMANDA DE LEÑA PARA USO RESIDENCIAL EN MÉXICO

TESIS

QUE PARA OBTENER EL GRADO ACADÉMICO DE

DOCTOR EN CIENCIAS

PRESENTA

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Me permito informar a usted que en la reunión ordinaria del Comité Académico del Posgrado en Ciencias Biológicas, celebrada el día 14 de Abril de 2008, se aprobó el siguiente jurado para el examen de grado de **DOCTOR EN CIENCIAS** del alumno **ADRIÁN GHILARDI ALVAREZ** con número de cuenta **504500552** con la tesis titulada: **"Análisis multi-escalar de los patrones espaciales de oferta y demanda de leña para uso residencial en México"**, realizada bajo la dirección del **DR. OMAR RAÚL MASERA CERUTTI:**

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RESUMEN

Palabras Clave: uso residencial de leña; patrones de oferta/demanda de leña; análisis y modelación espacial; Sistemas de Información Geográficos (SIG); extracción renovable/no-renovable de leña; emisiones de GEI; protocolo de Kyoto - MDL; propuestas de manejo sustentable; planeación energética.

En esta tesis se desarrolla un método de análisis multi-escalar y espacialmente-explícito para estudiar los impactos ambientales y socio-económicos asociados al uso tradicional de leña en México.

Históricamente, los estudios sobre oferta y demanda de leña se han concentrado en presentar sus resultados como valores agregados para un país o macro-región, o bien han sido el producto de multitud de estudios de caso conducidos sobre localidades particulares. Sin embargo, los impactos asociados al uso de leña se distribuyen de manera heterogénea en el espacio en función de la compleja interrelación entre los sistemas de oferta de leña y los factores que determinan la demanda para cada sitio en particular. Por lo tanto, los enfoques generalizados, como por ejemplo los balances nacionales, no dan información sobre la distribución espacial de las áreas más susceptibles a impactos negativos, mientras que los resultados de estudios de caso puntuales no son extrapolables, debido a que localidades adyacentes en el espacio pueden presentar situaciones muy diferentes.

En la presente investigación, se aplicó en una primera etapa un marco multi-criterio para analizar los municipios de México en función de siete variables o indicadores clave asociados al uso de leña y a la disponibilidad de recursos: número, densidad e incremento medio anual de usuarios de leña; porcentaje de hogares que utilizan leña; resiliencia en el consumo; tendencias de cambio de uso del suelo; y balance entre oferta y demanda de leña. El balance entre la oferta y la demanda de leña para todo el país -dato requerido con frecuencia por instituciones internacionales que buscan comparar los países del mundo con respecto al uso de combustibles de madera- resultó ampliamente positivo (165 millones de toneladas de leña en materia seca). Comparado con los países de África sub-sahariana y el sudeste asiático, México no es un país crítico en términos de uso de leña residencial y sus impactos asociados. Sin embargo, el análisis espacial identificó 304 municipios (de un total de 2,424 analizados), muchos con balances negativos o cercanos a cero, los cuales resultaron agrupados en 16 áreas críticas ó *hot spots*, donde viven 6.3 millones de usuarios de leña, aproximadamente el 25% de los usuarios totales de este combustible en el país. Dentro de éstas áreas destacan por el marcado déficit entre oferta y demanda, y por el número total de población usuaria de leña, las regiones Otomí y Mazahua en el Estado de México, la sierra norte de Puebla, la Huasteca Potosina-Veracruzana, y dos grupos de municipios al este y sur de las ciudades de Puebla y Xalapa respectivamente.

En una segunda etapa, se seleccionó un área crítica identificada en el análisis a nivel nacional: la Región Purhépecha en el estado de Michoacán, y se generó un modelo espacial a fin de identificar localidades con alto consumo de leña e insuficiente disponibilidad de recursos. Veinte localidades (de un total de 90 analizadas) fueron identificadas como críticas en función de los mismos indicadores seleccionados para el análisis previo. Las localidades identificadas resultaron distribuidas sobre municipios críticos según el análisis nacional, corroborando que ambos análisis son congruentes entre sí. Los resultados mostraron a su vez una gran variedad de situaciones entre las localidades analizadas, inclusive entre localidades vecinas dentro de un mismo municipio, lo que respalda el hecho de que los patrones de oferta y demanda de leña son muy específicos del sitio. El análisis permitió contar con estimativos robustos y estadísticamente confiables de la cantidad de leña por localidad extraída de manera no

renovable, el cual es un dato clave para calcular la línea de base para proyectos que buscan participar en el Mecanismo de Desarrollo Limpio del Protocolo de Kyoto, y que necesitan cuantificar las emisiones evitadas tomando en cuenta el cambio de biomasa no-renovable a biomasa renovable. Finalmente, datos de campo recolectados en localidades seleccionadas, mostraron que los sitios de extracción de leña se encontraron dentro de las áreas accesibles estimadas por el modelo para usuarios a pie o con animales de carga.

Se concluye que los resultados arrojados por el análisis a escala nacional son útiles para incorporar el uso tradicional de leña dentro de las agendas nacionales de planeación energética, al tiempo que facilitan concentrar los recursos disponibles sobre las áreas prioritarias. Por otra parte, los análisis orientados a identificar localidades individuales son útiles para ayudar en la implementación de acciones concretas de intervención, derivadas en última instancia de estrategias energéticas nacionales.

ABSTRACT

Keywords: residential fuelwood use; fuelwood supply/demand patterns; fuelwood hot spots; spatial analysis and modelation; Geographic Information Systems (GIS); non-renewable/renewable fuelwood extraction; GHG emissions; Kyoto protocol - CDM; sustainable management proposals; wood energy planning.

In this thesis, a spatially-explicit multi-scale method is proposed for assessing environmental and socio-economic impacts associated to traditional fuelwood use in Mexico.

Historically, supply demand studies have focused on showing aggregated results for a country or broad region; or on the contrary, they were case studies conducted on particular localities and villages. However, impacts associated to fuelwood use are heterogeneously distributed in space, given the complex relation between supply and demand patterns for each particular location. Thus, generalize approaches, as for example national balances, do not give information on the spatial distribution of those areas more susceptible to negative impacts, while localized case studies cannot be extrapolated, as neighbor localities may result radically different in terms of fuelwood use associated impacts.

In a first stage, a multi-criteria analysis was conducted in order to analyze Mexican counties following seven variables or indicators: number, density and annual increment of fuelwood users; percentage of households using fuelwood; resilience of consumption; trends in land use-land cover change; and balance between supply and demand. The national fuelwood balance -a key value when comparing countries- resulted widely positive (165 million tons per year). Compared to south east Asia and sub-Saharan African countries, Mexico is not a critical country in terms of fuelwood use and its associated impacts. However, the spatial analysis identified 304 counties (out of a total of 2,424); many of them with negative or close to zero balances, which resulted grouped in 16 clusters or fuelwood *hot spots*. Approximately 6.3 million fuelwood users live within these counties, 25% of total fuelwood users in Mexico in year 2000.

On a second stage, a fuelwood *hot spot* was selected: the *Purhepecha* Region in Michoacan State, and a grid-based model was developed in order to identified single localities with high fuelwood consumption and insufficient resources. Twenty localities (out of 90) were identified as critical following the same set of indicators used in the national assessment. Identified localities resulted distributed within critical counties previously identified in the national assessment, showing that both analyses are congruent between each other. A great variety of situations were found, even between neighbor localities, showing that fuelwood supply and demand spatial patterns are indeed site specific. The analysis also allowed to have a robust and statistically confident estimate of the non-renewable fraction of fuelwood extraction by locality, a key value for deriving baselines in business as usual (BAU) scenarios for carbon offset projects involving non-renewable biomass (NRB) estimates. Finally, ground-truthing efforts conducted so far, showed that extraction sites lye within accessible areas estimated by the grid-based model.

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, 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.

I. INTRODUCCIÓN

La bioenergía o energía derivada de la biomasa abarca toda la energía producida por combustibles orgánicos de origen biológico (bio-combustibles)[3]. Cuando los bio-combustibles provienen originalmente de especies vegetales leñosas, se les denomina combustibles de madera. La leña es un combustible de madera que conserva la estructura original de la madera (a diferencia del carbón vegetal, el licor negro, el metanol, los aceites pirolíticos, o los productos procedentes de la gasificación), y cuya combustión intencional puede aprovecharse como fuente de energía.

La leña representa una fuente de energía renovable ampliamente disponible, la cual puede jugar un rol muy importante en la transición a combustibles renovables, ya sea bajo un sistema de uso tradicional o moderno. Un paso fundamental a favor de diseñar estrategias nacionales para un uso sustentable de la leña, es entender los patrones espaciales de oferta y demanda, como así también los impactos ambientales, sociales y económicos asociados a su uso actual y esperado.

Alrededor del 60% del total de la madera extraída en el mundo se utiliza con fines energéticos, proporción que llega al 80% considerando por separado al conjunto de países en desarrollo (Trossero, 2002). Los combustibles de madera satisfacen el 7% del consumo de energía primaria a nivel mundial y el 15% cuando se considera solamente a los países en vías de desarrollo (Trossero, 2002). Se ha estimado que 2,390 millones de personas que habitan en países en vías de desarrollo dependen de combustibles de madera para cocinar, calentar agua y calefaccionarse (IEA, 2006). Se estima que para el año 2030 el consumo global de leña será de 1,501 millones de m3 (2030)[4] (IEA, 2006).

A mediados de la década de los setentas se desarrolló un modelo conocido como *fuelwood gap* (CEC, 1985; Eckholm, 1975; FAO, 1978; Shell, 1980) el cual pronosticaba, basándose en estimaciones muy generalizadas, que el consumo global de combustibles de madera, especialmente de leña, sobrepasaría la oferta en un período dramáticamente corto. Esto desataría una severa crisis energética que para el año 2000 habría afectado a la mitad de la población mundial (Anderson and Fishwick, 1984; De Montalambert and Clement, 1983; FAO, 1981). En términos generales, las premisas del modelo consideraban que la demanda de leña es igual al producto entre el consumo per cápita y la población total, por lo tanto, la demanda de leña aumentaba a una tasa igual al crecimiento poblacional. Por otra parte, la oferta de leña se estimaba en función del Incremento Corriente Anual (ICA) de los bosques según estadísticas oficiales (e.g. FAO, 1981; TWB, 1985), menos la pérdida de especies leñosas por procesos de deforestación y expansión agrícola ajenos a la extracción de leña[5]. Además de conducir a un déficit inevitable o *gap*, entre la oferta y la demanda de leña, el modelo consideraba que al intensificarse la escasez de leña por el aumento poblacional, se inducía a la degradación forestal, la cual a su vez era una causa principal de la falta de leña.

La alarma por las predicciones del modelo atrajo el flujo de fondos de ayuda e impulsó el desarrollo y la implementación de proyectos bioenergéticos bajo un enfoque *top-down*,

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[3] Se suele denominar habitualmente como “bio-combustibles” a dos de los bio-combustibles líquidos más comunes: el bioetanol y el biodiesel.

[4] Como referencia, 1,000,000 m^3 de madera (o 150.000 m^3 de carbón vegetal obtenido con técnicas poco eficientes) corresponden a un area entre 10,000 ha y 20,000 ha de una plantación madura con una densidad promedio. Un millón de m^3 de madera es equivalente aproximadamente a 10 petajoules (PJ) o 0.01 exajoules (EJ).

[5] Los supuestos subyacentes del modelo eran: 1) el consumo per cápita es una constante; 2) no existen combustibles sustitutos a la leña; 3) la oferta comercial de madera es un buen estimativo de la oferta de leña; 4) los valores agregados o promedios de escasez, para un país o un estado, son representativos de la situación a escala local (i.e. localidades y hogares); y 5) las fuentes de oferta de leña son accesibles para toda la población.

principalmente plantaciones energéticas de gran escala, difusión de estufas eficientes, y promoción de combustibles modernos (Openshaw, 1980). Hacia finales de los años 80´, con la experiencia acumulada por estos proyectos, se comenzaron a cuestionar las premisas que conllevaron a proponer la crisis de la leña: la situación generalizada de escasez no se perfilaba según las predicciones planteadas (Dewees, 1989; Foley, 1987; Leach and Mearns, 1988). Efectivamente, las predicciones sobre la crisis global de combustibles de madera no se estaban cumpliendo. Mas aún, evaluaciones conducidas en algunos países mostraron un balance agregado positivo[6] entre la oferta y la demanda de la leña (e.g. Foley (1987) para el caso de Mali; Dewees (1989) para el caso de Kenya).

Investigaciones conducidas a lo largo de los últimos 20 años, han demostrado que los patrones de oferta y demanda de combustibles de madera son complejos y muy específicos del sitio (Arnold *et al.*, 2003; Dewees, 1989; Foley, 1987; Leach and Mearns, 1988; Lelé, 1993; Mahapatra and Mitchell, 1999; Masera, 1994; RWEDP, 1997, 2000); por lo tanto, los enfoques generalizados, como por ejemplo los balances nacionales, no son recomendables para evaluar la situación general de un país o región con respecto a la relación entre la oferta y la demanda de combustibles de madera. Más que una crisis generalizada, actualmente se reconoce la existencia de áreas críticas mas o menos puntuales, las cuales se presentan distribuidas de manera heterogénea en el espacio en función de la compleja interrelación entre los sistemas de oferta de combustibles de madera y los factores que determinan la demanda para cada sitio en particular (Arnold *et al.*, 2003; Mahapatra and Mitchell, 1999; RWEDP, 2000)[7].

Enfocándonos en el uso residencial de leña, la oferta para un sitio o área específica (e.g. hogar, localidad, municipio) es la suma de a) la oferta forestal , b) la oferta que proviene de los sistemas de uso del suelo no forestales, y c) la oferta que se genera como sub-producto de otras actividades (e.g. tala comercial, construcción, etc.) (Agarwal, 1986; Masera, 1993, 1994; Morse, 1984; RWEDP, 1993b).

Los factores arriba mencionados, determinan la oferta potencial de leña para un área o sitio de estudio. Sin embargo la oferta disponible o efectiva es una función del acceso físico, legal y técnico a la oferta potencial (Masera, 1994; Munslow *et al.*, 1988). El acceso físico está relacionado con variables como la distancia a los puntos de demanda y la topografía (e.g. pendientes, red de caminos, barreras naturales). El acceso legal o social, es la capacidad de usar o beneficiarse de un recurso productivo (Masera, 1994). Éste depende de los patrones de tenencia de la tierra, y de reglas o acuerdos locales sobre el uso del suelo. A su vez, los acuerdos sobre uso del suelo dependen del tipo de actividad extractiva: recolección de subsistencia, o corte de árboles para venta de leña. La accesibilidad técnica se refiere a la capacidad de acceder y aprovechar el recurso cuando el acceso físico y legal está garantizado: así por ejemplo, la falta de un medio de trasporte o la imposibilidad de pagar el combustible son una limitante para el aprovechamiento del recurso (Farrow and Nelson, 2001).

La demanda de leña está determinada por a) las necesidades energéticas de la unidad de análisis (i.e. hogar, pequeñas industrias, etc.), b) los dispositivos de uso final empleados para satisfacer esas necesidades (i.e. fogones, estufas eficientes, hornos, etc.), y c) la porción de las necesidades energéticas que son cubiertas mediante el uso de la leña (Masera, 1994). Los tres factores recién mencionados son función de variables ambientales (Bhatt *et al.*, 1994; Díaz, 2000; Leach and Gowen, 1987; Masera, 1994), demográficas (Leach and Gowen, 1987),

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[6] En su expresión más simple, el balance se calcula como la oferta menos la demanda.

[7] Así por ejemplo, una región cuya demanda agregada excede a la oferta, puede albergar áreas en donde no existe déficit alguno. Por el contrario, comunidades deficitarias existen dentro de regiones cuyo balance energético total con respecto a la leña es positivo.

económicas (Islam, 1984; Leach, 1988; Munslow *et al.*, 1988), culturales (Masera, 1994; Navia, 1992), y técnicas (Evans, 1987; Leach and Gowen, 1987; Tinker, 1987).

I.1 Descripción del problema e importancia del proyecto

Las revisiones más recientes sobre el uso de leña en el mundo (Arnold *et al.*, 2003; IEA, 2006; Persson, 2001) han destacado la necesidad de "entender bajo qué circunstancias la extracción de leña puede ser una causa de deforestación y bajo qué circunstancias la población puede sufrir dificultades en el abasto de leña" (Persson, 2001, página 11). El Programa Regional para el Desarrollo de la Dendroenergía en Asia (RWEDP)[8], el de mayor envergadura e impacto para países en desarrollo, ha puesto especial énfasis en la necesidad de "contar con análisis que incorporen la heterogeneidad espacial de los patrones de uso de leña a diferentes escalas y niveles de agregación" (RWEDP, 2000, página 75).

Una metodología o marco de análisis semejante sería de fundamental importancia para abordar el problema de la especificidad del sitio de los patrones de oferta y demanda de leña, y poder presentar resultados y estimaciones confiables como insumos para la planeación y el diseño de estrategias energéticas a diferentes escalas administrativas.

I.2 Objetivo del proyecto

A fin de proponer una alternativa a la problemática recién planteada, se definió como objetivo central y general del presente proyecto, desarrollar una metodología que permita abordar y eventualmente resolver aquellas preguntas claves con respecto al uso residencial de leña en países en desarrollo, enfocándose en México como estudio de caso: ¿qué localidades de México se encuentran en peores condiciones en cuanto al abasto de leña o al impacto ambiental asociado al uso de este recurso?, ¿como se distribuyen y agrupan éstas localidades en el territorio?, ¿que variables determinan la distribución espacial de éstas situaciones críticas?, y finalmente, si éstas localidades críticas existieran, ¿serían susceptibles de ser identificadas partiendo de un análisis que abarque todo el territorio nacional?

Es necesario resaltar que el desarrollo de una metodología o modelo es el objetivo en sí mismo, independientemente de las preguntas subyacentes, las cuales podrían ligarse eventualmente a un sistema de hipótesis. Esto se definió así desde un principio justamente por la falta de métodos disponibles para responder las preguntas planteadas, pero sobretodo porque es la necesidad de contar con metodologías de análisis, como se ha expuesto formalmente el problema en la literatura.

Por último, en cada uno de los tres capítulos centrales de la presente tesis se plantean objetivos generales y específicos que no es necesario anticipar.

En síntesis, durante el presente proyecto se desarrolló un modelo para articular la heterogeneidad local de los patrones de uso de leña, con las escalas regional y nacional, a fin de contar con un análisis integral del recurso.

Se argumentó que el problema debe ser enfrentado a través de una modelación que permita representar espacialmente al conjunto de variables claves asociadas a los patrones de uso de leña (e.g. accesibilidad, productividad, densidad de usuarios, clima, etc.). Un conjunto tal de variables supuso la síntesis de un acervo importante de información estadística y de estudios de caso.

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[8] Regional Wood Energy Development Programme in Asia

Los dos enfoques principales que se utilizaron durante el proyecto fueron la multi-escalaridad y la representación espacial de la información. Este tipo de enfoques han sido identificados como uno de los componentes básicos para promover el uso sustentable de los recursos naturales (Cash and Moser, 2000; Gibson *et al.*, 2000; Kates *et al.*, 2001; Masera *et al.*, 2000). La meta principal de la lógica multi-escalar fue obtener resultados según diferentes escalas espaciales y con diferente grado de resolución, permitiendo la selección sucesiva de áreas de análisis cada vez más detalladas. Como se argumentó anteriormente, los estudios sobre uso de leña basados en promedios agregados pueden conducir a conclusiones erróneas. La representación espacial de la información es un método para trabajar con valores desagregados por unidad espacial de análisis. La relación entre los dos enfoques propuestos se articuló a través del uso de unidades espaciales de análisis básicas (BSU, por sus siglas en inglés) definidas para cada una de las escalas de trabajo.

I.3 Antecedentes metodológicos

El origen del presente proyecto es un reporte de la FAO del año 2003: Mapeo Integrado de la Oferta y la Demanda de Combustibles de Madera (WISDOM)[9], desarrollado por Masera y colaboradores, donde se combinó información geográfica y estadística sobre la producción y el consumo de leña para definir áreas según un índice de prioridad a escala nacional. La metodología fue desarrollada en principio para ayudar en la planificación estratégica del uso sustentable de la leña a nivel de país y constituye una parte importante del marco teórico de este proyecto.

I.4 El uso de leña residencial en México

En México, alrededor de 18 millones de habitantes disponen únicamente de leña como combustible para cocinar, calentar agua y calefaccionarse y otras 7 millones la usan en conjunto con el gas licuado a presión (Gas LP) (Díaz, 2000; INEGI, 2000). La leña que se utiliza en México satisface el 11% del total de la demanda energética total, el 46% de la demanda energética residencial, y el 80% de la demanda energética del sector rural (Díaz, 2000; SENER, 2001).

Sólo dos sectores en México utilizan leña como combustible: a) el sector residencial (INEGI, 2000) y b) el sector informal de pequeñas industrias (Masera and Navia, 1997). El consumo del sector residencial para el año 2000 se estimó en 320 petajoules (PJ) (Díaz, 2000; INEGI, 2000). Éste representa un volumen equivalente a 32 millones de m^3 de madera, valor 3 veces superior al total de la madera talada anualmente con fines comerciales (madera en rollo, astillas, pulpa y papel) (SEMARNAT, 2004). El consumo estimado de las pequeñas industrias es de aproximadamente 31 PJ (Masera and Navia, 1997).

El uso de leña en México responde en términos generales al patrón denominado “tradicional”, caracterizado por: 1) su heterogeneidad espacial, 2) concentrarse en el sector campesino y residencial, 3) el uso extendido de tecnologías locales y 4) prácticas y sistemas de extracción muy diversos (e.g. manejo de regeneración vegetativa, manejo de acahuales, extracción selectiva, extracción aleatoria, etc.) (Masera, 1994).

La leña en México se colecta o se compra normalmente en mercados locales. Aunque las fuentes de oferta del recurso son en extremo diversas, se estima que un gran porcentaje de la leña se colecta en áreas forestales (comerciales y no comerciales), de tierras agrícolas en

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[9] Woodfuel Integrated Supply Demand Overview Mapping (Masera *et al.*, 2003).

regeneración, y de regiones áridas con cobertura arbustiva (Del Amo-Rodríguez, 2002; Masera, 1996; Masera and Navia, 1997). Las especies preferidas para leña no necesariamente son de importancia comercial, y muchas veces se utilizan sólo como combustible (Del Amo-Rodríguez, 2002; Díaz, 2000; Puentes, 2002).

I.5 Estructura de la tesis

La presente tesis se organizó en 3 capítulos centrales, una discusión y conclusión general y seis anexos.

El capítulo II consta de un artículo publicado en la revista *Biomass and Bioenergy*, el cual es una re-formulación del reporte de la FAO del 2003 (Masera *et al.*, 2003), donde se describe en términos generales la metodología WISDOM junto a tres estudios de caso. Posteriormente se mencionan tres nuevos estudios de caso para Brasil, Sudeste Asiático y Este de África que fueron publicados como reportes en años sucesivos.

El capítulo III consta de otro artículo publicado en la misma revista, donde se aplica el modelo WISDOM en México, y en el cual se obtuvo como resultado principal un número de áreas críticas formadas cada una por grupos adyacentes de municipios. Se utilizó un enfoque metodológico mejorado que incluye, entre otros, el uso de un marco multi-criterio, nuevas variables de entrada, y la depuración completa de la base de datos geo-referenciada a partir del censo por localidad del INEGI y de una recopilación extensiva sobre estudios de caso que reportaron valores de productividad para diferentes clases de cobertura del suelo. Posteriormente al artículo, se presenta una seria de mapas temáticos como producto del análisis a escala nacional que no pudieron ser incluidos en el artículo.

El capítulo IV consta de un artículo sometido a la revista *Journal of Environmental Management*, el cual explora un nuevo enfoque metodológico, basado en la metodología WISDOM aplicada a escala nacional, pero orientado a identificar localidades particulares dentro de un área crítica previamente identificada en el capitulo anterior. Finalmente se adjuntan mapas temáticos con resultados de interés sobre la región de estudio junto a información relevante que no se incluyó en el artículo.

El último capítulo (V) consta de una discusión general sobre los resultados de los tres capítulo anteriores junto a las conclusiones principales sobre el alcance de la metodología propuesta y las direcciones futuras de investigación.

Al final del documento de adjuntaron seis anexos considerados relevantes, dentro de los cuales se incluyeron dos nuevos artículos, uno publicado y otro sometido, los cuales están directamente relacionados con los resultados del presente proyecto.

II. EL MODELO *WISDOM*: UNA HERRAMIENTA PARA EL ANÁLISIS ESPACIAL DE LA OFERTA Y DEMANDA DE COMBUSTIBLES DE MADERA

II.1 WISDOM: A GIS-based supply demand mapping tool for woodfuel management

A continuación se adjunta el artículo publicado en la revista *Biomass and Bioenergy*, volumen 30, año 2006.[10]

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[10] Se puede obtener una copia en formato PDF del artículo desde la página Web de la revista: http://www.elsevier.com/wps/find/journaldescription.cws_home/986/description#description *"Search through the articles of this journal"*. Si no cuenta con el permiso de acceso, favor de contactarse con aghilardi@oikos.unam.mx y le será enviada una copia en formato PDF a la brevedad.

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WISDOM: A GIS-based supply demand mapping tool for woodfuel management

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Abstract

In this paper, it is argued that adequately assessing the implications of the current patterns of woodfuel production and use, and the sustainable potentials of woodfuel resources, requires a holistic view and a better knowledge of the spatial patterns of woodfuel supply and demand. There is a need to conduct multi-scale spatially explicit analyses of woodfuel supply and demand that are able to articulate local heterogeneity at the regional and national levels. Studies that provide full-country coverage and are based on consistent integration of data at lower geographical scales are woefully lacking. This paper describes the Woodfuel Integrated Supply/Demand Overview Mapping model (WISDOM). This is a GIS-based tool, aimed at analyzing woodfuel demand and supply spatial patterns from a new perspective that includes: (a) the assembling of existing but dispersed information into single data sets, (b) a modular integration of these data sets, based on the analysis of key variables associated with woodfuel demand and supply patterns, and (c) a multiple-scale and spatially explicit representation of the results, in order to rank or highlight areas in which several criteria of interest coincide. The final objective of WISDOM is to assess the sustainability of woodfuel as a renewable and widespread energy source, while supporting strategic planning and policy formulation. Three case studies for Mexico, Slovenia, and Senegal illustrate the practical implementation and innovative results of using WISDOM.

Keywords: Fuelwood priority areas; Fuelwood planning; Sustainability assessment; Data analysis; Mexico; Slovenia; Senegal

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Abbreviations: ABF, Association Bois de Feu, Senegal; CDM, Clean Development Mechanism (UNFCCC); CHP, combined heat and power; CR, Rural Communities (counties of Senegal); CSE, Centre de Suivie Ecologique of Dakar, Senegal; CSE, EROS Center for Ecological Monitoring (USGS); DEM, digital elevation model; Digital Chart of the World, Environmental Systems Research Institute, Inc. (ESRI) product: http://www.maproom.psu.edu/dcw/ (Last visited on 19th December 2005); EROS, Earth Resources Observation & Science (USGS); FAO, Food and Agriculture Organization of the United Nations (UN); FPI, Fuelwood Priority Index; FRA RSS, Remote Sensing Survey of the Forest Resources Assessment (FAO); GHG, Greenhouse Gases; GIS, Geographic Information System; GTOPO 30, Global digital elevation model (DEM) with a horizontal grid spacing of 30 arc; IUCN, International Union for the Conservation of Nature; KO, Cadastral Communities (counties in Slovenia); LANDSAT, United States satellite used to acquire remotely sensed images of the Earth's land surface and surrounding coastal regions; LCCS, Land Cover Classification System of the AFRICOVER Project (FAO); LPG, Liquefied Petroleum Gas; LU/LC, Land use/Land cover; PSACD, Programme Sectoriel d'Appui au Combustible Domestique (Senegal); SEMIS, Bureau d'étude Sénégalais, Dakar, Senegal; SFS, Slovenia Forest Service; SWEIS, Slovenia Wood Energy Information System; TREES II, Tropical Ecosystem Environment Observations by Satellite (II stands for second phase); UNFCCC, United Nations Framework Convention on Climate Change; USAID/DAT, *Direction de l'Aménagement du Territoire*, Dakar, Senegal. United States Agency for International Development (USAID); USGS, United States Geological Service; WISDOM, Woodfuel Integrated Supply/Demand Overview Mapping; WPI, Woodfuel Priority Index; WSC, woodfuel supply capacity

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1. Introduction

When used in a sustainable way, biomass represents a renewable energy source which is widely available. Bioenergy can play a major role in the expected worldwide transition to renewables, both in developed and developing countries [1,2]; and have significant positive impacts on climate change, by offsetting fossil fuel emissions. Estimates of the bioenergy production potential in 2050, reaches a maximum of 1.135 ZJ yr^{-1} [1,2]. For comparison, the global primary energy consumption in 2001 was 420 EJ [3]. One step that is needed in order to design national strategies for sustainable biomass energy use and exploitation is to understand in detail, the current spatial patterns of biomass demand and supply over a country.

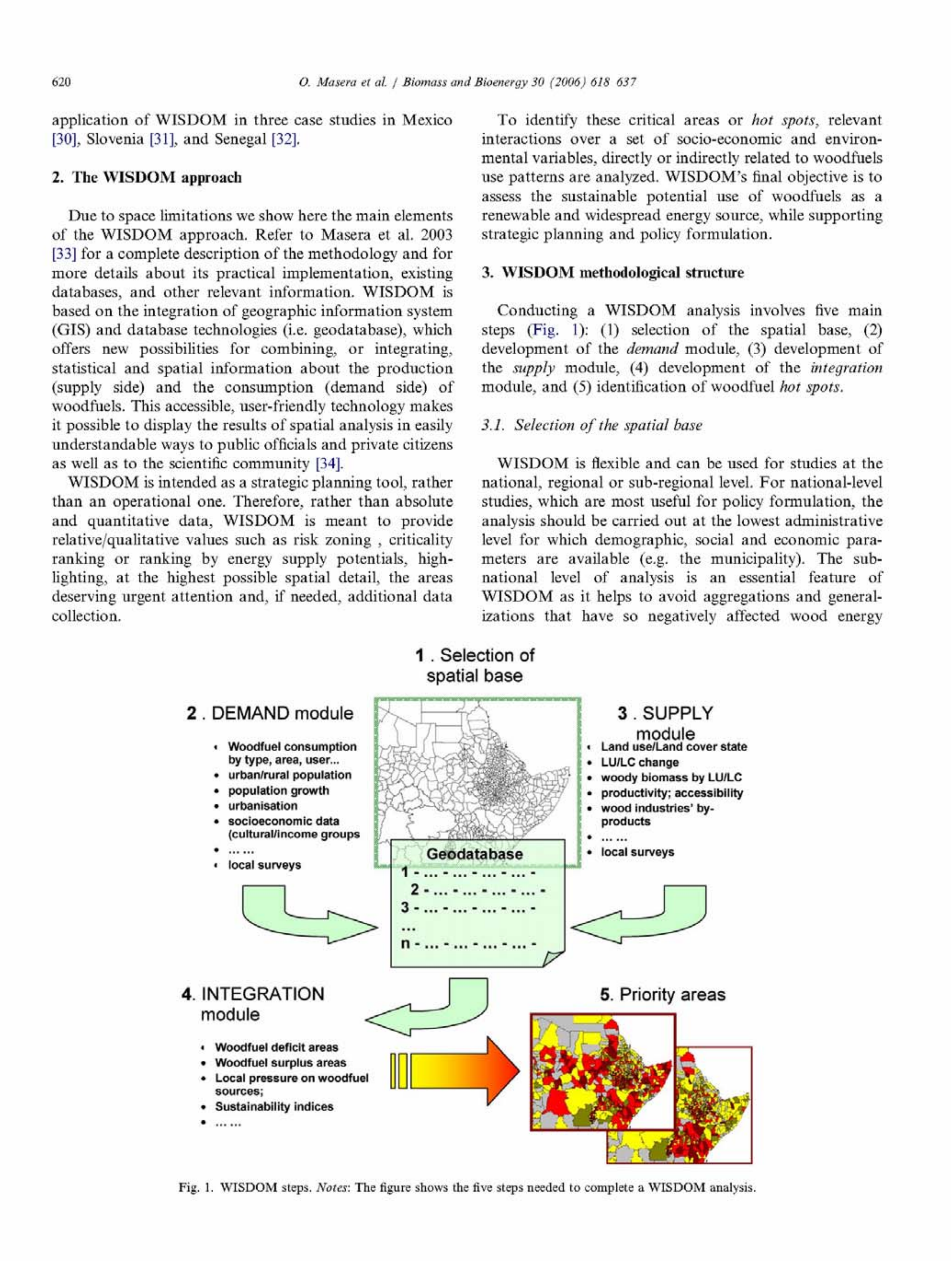
Currently, about 60% of the wood removed from around the world is used for energy purposes. For the group of developing countries this amount rises to 80% [4]. Woodfuel is one of the main forest products, in many situations, the major product [5]. For a comprehensive definition of the term "woodfuel", please refer to FAO's Unified Wood Energy Terminology [6]. Woodfuels satisfy 7% of the world primary energy consumption, and 15% when considering the group of developing countries [4]. The International Energy Agency estimated that approximately 2.4 billion people living in developing countries depend on woodfuels for cooking, heating, and boiling water [7]. FAO projections to 2030 predict a slow decline in the global annual fuelwood consumption from 1.611 km^3 (2000) to 1.501 km^3, whereas charcoal consumption is expected to grow from 46 Mt (2000) to 76 Mt in 2030 [8]. For comparison, 1 hm^3 of wood (or 150 dam^3 of charcoal obtained with poor techniques) corresponds to an area between 100 km^2 and 200 km^2 of a mid-density mature plantation. One hm^3 of wood is equivalent to approximately 10 PJ. As seen by these numbers, woodfuel plays an indubitable role as an energy source; however, its patterns of demand and supply, and its associated social, economic and environmental impacts are still poorly understood.

Historically, reliance on very general and aggregated information on woodfuels has led to misleading conceptions about the effect of woodfuel use on the environment and its sustainability: from pointing to woodfuels as major direct causes of deforestation and forest degradation (e.g. "woodfuel crisis" approach [9 11]) [12 14], to the denial of any significant influence of woodfuel collection in these processes [15,16]. These types of assessments have also resulted in poor planning and ineffective implementation of projects. The research conducted in the last decade, including comprehensive field studies and projects have shown that woodfuels demand and supply patterns are rather complex and very site specific [17 25]. This characteristic has shifted the early thinking of a general fuelwood crisis to the understanding that critical areas vary from place to place [22,23,25]. 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 [22,23,25]. In this article, the terms woodfuel "supply" and woodfuel "production" are used synonymously, as are woodfuel "demand" and woodfuel "consumption", since they are used in a technical as opposed to an economic sense.

To cope with these problems, thorough local studies have been implemented (e.g. area-based woodfuel flows analysis: see [26] for the case of Mexico). The results of these local investigations are then expanded at national level to guide energy actions and interventions [23]. Although these approaches have proven the heterogeneity of local situations, and provide the information needed to understand wood energy situations at the local level, they are expensive and time consuming. They also tend to be limited to small areas, and to be sporadic, thus failing to convey the national perspective needed for the design of effective national policies, for completing national inventories for greenhouse gases, or for estimating the national potential of woodfuels as a renewable energy source. Moreover, obtaining exact measures of woodfuel deficits (as in studies conducted using the traditional fuelwood gap model [27,28]) presents severe methodological and financial challenges, particularly considering the scarce resources normally allocated to this specific sector [15]. Still little is known, for example, about the amounts, extent, geographical location and dynamics of wood supplies: from plantation strategies, to traditional wood collection and harvesting methods [29].

In this paper, it is argued that adequately assessing the implications of the current patterns of woodfuel production and use, and the sustainable potential of woodfuel resources, requires a holistic view and a better knowledge of the spatial patterns of woodfuel supply and demand. There is a critical need of planning tools that allow users to integrate data from various sectors and to conduct multi scale spatially explicit analyses of woodfuel supply and demand that are able to articulate the local heterogeneity into the regional and national levels. Studies that provide full-country coverage and are based on a consistent integration of data at lower geographical scales are woefully lacking. Such studies should be oriented to identify priority areas and *hot spots* within a country or a broad region. In a second step, more in-depth analyses can be conducted within priority areas, allowing a more efficient use of scarce available resources.

This paper introduces the Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM), a spatially explicit method for determining woodfuel priority areas. WISDOM has been developed by FAO, in cooperation with the Center for Ecosystem Research of the National Autonomous University of Mexico (UNAM). WISDOM has been formulated as a planning tool and a methodology to provide country-wide synoptic views of local wood energy supply and demand patterns based on the consistent integration of forestry, energy and socio-economic data and information. We also summarize the results of the



application of WISDOM in three case studies in Mexico [30], Slovenia [31], and Senegal [32].

2. The WISDOM approach

Due to space limitations we show here the main elements of the WISDOM approach. Refer to Masera et al. 2003 [33] for a complete description of the methodology and for more details about its practical implementation, existing databases, and other relevant information. WISDOM is based on the integration of geographic information system (GIS) and database technologies (i.e. geodatabase), which offers new possibilities for combining, or integrating, statistical and spatial information about the production (supply side) and the consumption (demand side) of woodfuels. This accessible, user-friendly technology makes it possible to display the results of spatial analysis in easily understandable ways to public officials and private citizens as well as to the scientific community [34].

WISDOM is intended as a strategic planning tool, rather than an operational one. Therefore, rather than absolute and quantitative data, WISDOM is meant to provide relative/qualitative values such as risk zoning , criticality ranking or ranking by energy supply potentials, highlighting, at the highest possible spatial detail, the areas deserving urgent attention and, if needed, additional data collection.

To identify these critical areas or *hot spots*, relevant interactions over a set of socio-economic and environmental variables, directly or indirectly related to woodfuels use patterns are analyzed. 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.

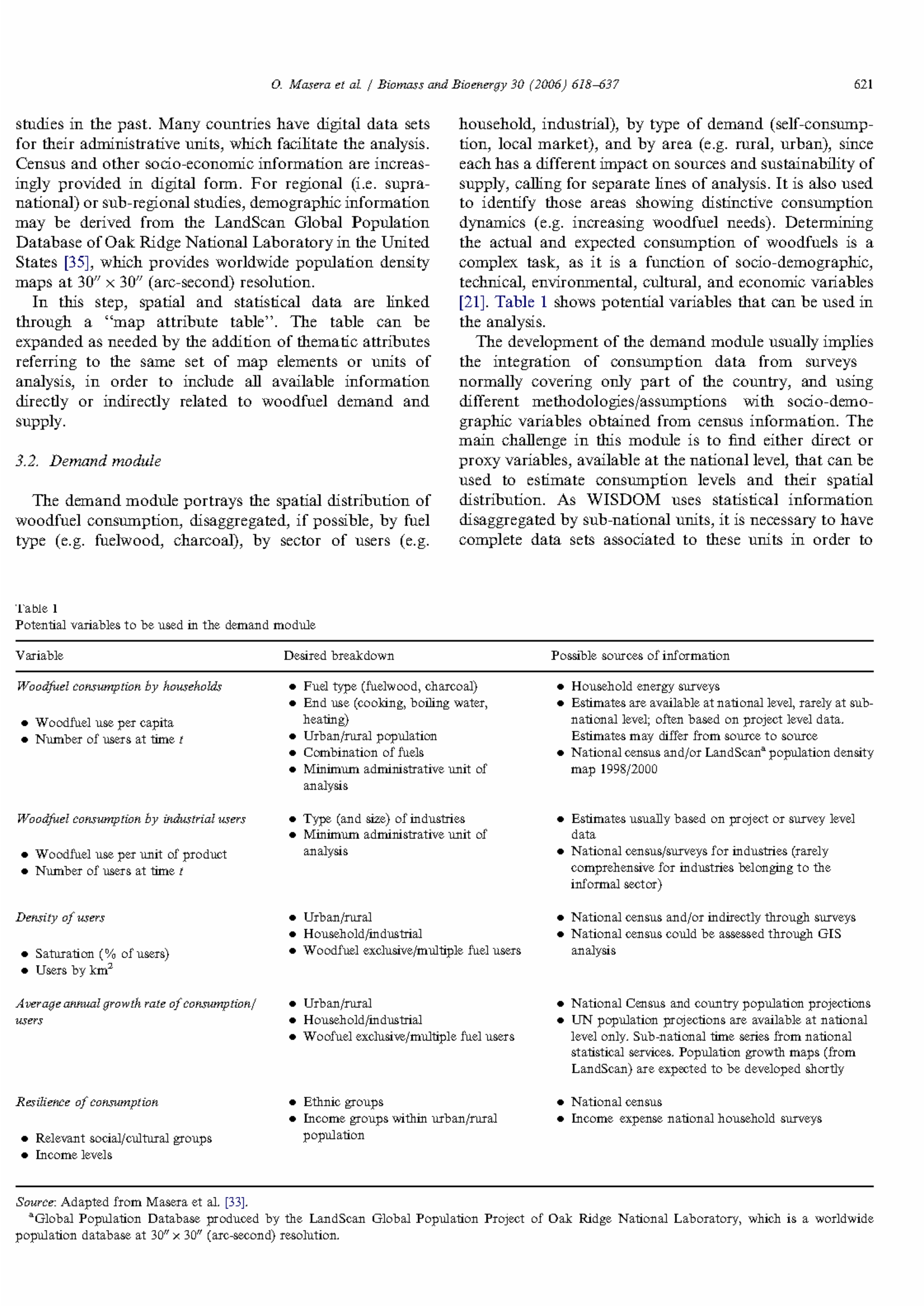
3. WISDOM methodological structure

Conducting a WISDOM analysis involves five main steps (Fig. 1): (1) selection of the spatial base, (2) development of the *demand* module, (3) development of the *supply* module, (4) development of the *integration* module, and (5) identification of woodfuel *hot spots*.

3.1. Selection of the spatial base

WISDOM is flexible and can be used for studies at the national, regional or sub-regional level. For national-level studies, which are most useful for policy formulation, the analysis should be carried out at the lowest administrative level for which demographic, social and economic parameters are available (e.g. the municipality). The sub-national level of analysis is an essential feature of WISDOM as it helps to avoid aggregations and generalizations that have so negatively affected wood energy

Fig. 1. WISDOM steps. *Notes*: The figure shows the five steps needed to complete a WISDOM analysis.



studies in the past. Many countries have digital data sets for their administrative units, which facilitate the analysis. Census and other socio-economic information are increasingly provided in digital form. For regional (i.e. supra-national) or sub-regional studies, demographic information may be derived from the LandScan Global Population Database of Oak Ridge National Laboratory in the United States [35], which provides worldwide population density maps at 30″ × 30″ (arc-second) resolution.

In this step, spatial and statistical data are linked through a "map attribute table". The table can be expanded as needed by the addition of thematic attributes referring to the same set of map elements or units of analysis, in order to include all available information directly or indirectly related to woodfuel demand and supply.

3.2. Demand module

The demand module portrays the spatial distribution of woodfuel consumption, disaggregated, if possible, by fuel type (e.g. fuelwood, charcoal), by sector of users (e.g. household, industrial), by type of demand (self-consumption, local market), and by area (e.g. rural, urban), since each has a different impact on sources and sustainability of supply, calling for separate lines of analysis. It is also used to identify those areas showing distinctive consumption dynamics (e.g. increasing woodfuel needs). Determining the actual and expected consumption of woodfuels is a complex task, as it is a function of socio-demographic, technical, environmental, cultural, and economic variables [21]. Table 1 shows potential variables that can be used in the analysis.

The development of the demand module usually implies the integration of consumption data from surveys normally covering only part of the country, and using different methodologies/assumptions with socio-demographic variables obtained from census information. The main challenge in this module is to find either direct or proxy variables, available at the national level, that can be used to estimate consumption levels and their spatial distribution. As WISDOM uses statistical information disaggregated by sub-national units, it is necessary to have complete data sets associated to these units in order to

Table 1
Potential variables to be used in the demand module

Variable	Desired breakdown	Possible sources of information
Woodfuel consumption by households • Woodfuel use per capita • Number of users at time *t*	• Fuel type (fuelwood, charcoal) • End use (cooking, boiling water, heating) • Urban/rural population • Combination of fuels • Minimum administrative unit of analysis	• Household energy surveys • Estimates are available at national level, rarely at sub-national level; often based on project level data. Estimates may differ from source to source • National census and/or LandScan[a] population density map 1998/2000
Woodfuel consumption by industrial users • Woodfuel use per unit of product • Number of users at time *t*	• Type (and size) of industries • Minimum administrative unit of analysis	• Estimates usually based on project or survey level data • National census/surveys for industries (rarely comprehensive for industries belonging to the informal sector)
Density of users • Saturation (% of users) • Users by km^2	• Urban/rural • Household/industrial • Woodfuel exclusive/multiple fuel users	• National census and/or indirectly through surveys • National census could be assessed through GIS analysis
Average annual growth rate of consumption/users	• Urban/rural • Household/industrial • Woofuel exclusive/multiple fuel users	• National Census and country population projections • UN population projections are available at national level only. Sub-national time series from national statistical services. Population growth maps (from LandScan) are expected to be developed shortly
Resilience of consumption • Relevant social/cultural groups • Income levels	• Ethnic groups • Income groups within urban/rural population	• National census • Income expense national household surveys

Source: Adapted from Masera et al. [33].

[a] Global Population Database produced by the LandScan Global Population Project of Oak Ridge National Laboratory, which is a worldwide population database at 30″ × 30″ (arc-second) resolution.

"spatialize" the information over the maps. Gaps in the data may be filled in three ways: (1) by the use of proxy variables to "spatialize" discontinuous values (e.g. using rural population as a proxy for woodfuel users); (2) by extrapolating information available at the project level, to the entire study region (i.e. to extrapolate fuelwood consumption per capita). This procedure may be valid in cases where data does not need to be highly accurate or where woodfuel consumption estimates cover at least representative regions or situations within the study area; and (3) by filling specific or critical data gaps with new data coming from field surveys. This option could be very expensive, so the surveys need to be carefully designed, to minimize the cost and effort for a given precision level. Different woodfuel survey methodologies can be used for these purposes [25,36].

Several criteria can be set to determine priority areas in terms of woodfuel demand. For example, one might be interested in areas that show: (a) high woodfuel consumption; (b) high density of woodfuel users; (c) high growth rates of woodfuel consumption or users, either by households or industrial users; (d) high resilience of woodfuel demand (in terms of cultural attachment to fuelwood use, represented for example by the percentage of ethnic population).

The precise criteria, and the corresponding prioritization of areas, will depend on the specific objective of the study. For example, the study may be intended to identify places with large potential market opportunities for new technologies or places with major health impacts associated with the use of open fires for cooking.

3.3. *Supply module*

Having access to reliable data on woodfuel supply has been historically one of the main challenges in wood energy analysis. For this reason we will be more explicit in this section. To the extent allowed by the existing information, the supply module should provide a spatial representation of all natural and planted woodfuel sources, their current stock (volume of biomass), their change over time and their productive capacities. Thus the analysis *is not* restricted to natural forests, but also encompasses, plantations, trees outside forest, woodlands, shrubs, live hedges and any other main source of woodfuels. The main, and often the only, sources of information for developing this module are national forest inventories, since detailed surveys of biomass stocking and productivity covering non-forest land-use classes are still rare events. In most cases, stocking and productivity for non-forest woodfuel sources (shrubs, agricultural plantations, agro-forestry practices, etc.) will be inferred or guesstimated. Given the paucity of data on non-forest classes, the development of this module will usually rely on local studies, even if of limited coverage, and experts' opinions.

As with the demand module, it is essential to use disaggregated statistics referring to small spatial units of analysis rather than aggregated averages. Table 2 shows the potential variables to be used for the development of the supply module. In general terms, it may be assumed that the woodfuel supply capacity (WSC) of an area is a function of several factors which include, among others: (a) land use/land cover and relative changes; (b) biomass stocking and productivity of trees, shrub and herbaceous species; and (c) accessibility.

Detailed land use/land cover inventories are still scarce but increasingly available at the national and international level. An interesting example is the FAO AFRICOVER Project over East and Central Africa countries. Promising features of AFRICOVER products are the wall-to-wall coverage of all countries at a good level of detail (scale 1:100,000 1:200,000) and the associated Land Cover Classification System (LCCS), which represents well the wide variety of low-density vegetation types characteristics of African landscapes, and offers a good basis for the estimation of woody biomass stocking [37].

Concerning land cover change, national deforestation rates are available in countries that regularly conduct monitoring studies. However, only few tropical countries undertake regular monitoring studies from which sub-national change patterns can be derived (India, Brazil limited to Legal Amazon have some, but there are none for Africa for example). Richer information on land cover changes was produced for the tropical belt, by region and main ecological zones. Other sources of information include the Remote Sensing Survey of the Forest Resources Assessment (FRA RSS) carried out during the 1990 Assessment, and continued in the 2000 Assessment [38 40,42]. This study produced highly consistent information on the land cover change processes and trends for the periods 1980 1990 and 1990 2000 through the analysis of satellite time series over a 10% statistical sample of tropical land. Important information from this study is the biomass flux diagram, which provides a useful indication on the loss or gain of woody biomass associated with each change in land cover. The FRA RSS analyzed 117 sampling units, each of them covering an entire Landsat scene (185 × 185 km). Additional evidence on the change in land cover occurring in the humid tropical regions over the period 1990 1997 has recently been produced by the TREES II Project of the European Joint Research Center on the basis of a statistical sample of high-resolution satellite images covering the dense forest formations of the humid tropics [37,41]. The TREES High Resolution Study analyzed 93 sampling units, 39 of which covering full Landsat scenes and 54 covering quarter scenes (approximately 100 × 100 km). Neither of the two studies produced country-level results, but each of the sampling units analyzed in these surveys, which vary in size between 10,000 and 34,225 km^2, may contribute some interesting insights into the local patterns of change.

Information on biomass stockings and productivity of natural forests and plantations may be derived through the integration of land cover information with conventional

Table 2
Potential variables to be used in the supply module

Variable	Desired breakdown	Possible sources of information
Land use/land cover class	All land use/land cover classes must be considered (including both forest and non-forest classes)	National Forest Inventories, e.g. AFRICOVER mapping in Africa using FAO's Land Cover Classification System [37]
Land use/land cover change	Crude deforestation rates should be avoided; land cover transitions (i.e. using land use transition matrices) are well suited for this type of analysis	National monitoring studies; large-scale studies such as FAO's Global Forest Resources Assessment remote-sensing survey [38 40]; TREES II high-resolution survey [41]
Woody biomass stocking by land use/land cover	Biomass stocking for all land use/land cover classes including croplands, shrublands, etc.	Forest inventory data (volume expanded to total biomass); inference and extrapolation from detailed studies to include non-commercial species used as woodfuels
Average biomass production by land use/land cover class	Productivity indices for all land use/land cover classes	Forest inventory data (yield expanded to total biomass); non-forest biomass surveys (still rare); inference and extrapolation from detailed studies; agro-ecological zoning
By-products of primary and secondary wood processing industries	Type and quantity of by-products (residues) produced by main industrial processes (by unit of processed main product) Spatial distribution of industrial units	National statistics on industrial production. Chamber of commerce data on size and distribution of wood processing industries
Accessibility	Adjust total area by legal reasons (e.g. protected areas), for physical reasons (e.g. slope, distance, natural barriers) and for economic reasons (e.g. tenure fragmentation making the extraction uneconomic)	Legal access: national or international maps of protected areas, such as those of the World Conservation Union (IUCN)
		Physical access: digital elevation models (DEMs) and route maps (e.g. products derived from the Digital Chart of the World) Economic access: cadastral data on forest ownership; average property size and fragmentation

Source: Adapted from Masera et al. [33].

forest inventory data (volume and yield) [43]. For instance, the LCCS applied in several African countries, which is based on classifiers independently describing three vegetation layers (trees, shrubs, and herbaceous), may be combined with local volume and yield estimates to produce biomass density maps. Rarer are stocking and productivity estimates for non-forest formations such as scrublands, homestead gardens, windbreaks, roadside trees, farmland trees, etc., which may represent important woodfuel sources for the rural population [24,43 45]. Usually this aspect will need to be covered by inference and extrapolation of detailed studies conducted at the project or micro-regional level.

Access to woodfuels must be considered when calculating the WSC of an area [30,40]. As with other variables, accessibility results should be disaggregated by minimum units of analysis, following each scale of analysis (Table 2). Physical accessibility may be defined in a Geographic Information System (GIS) through the use of slope information from terrain models (e.g. GTOPO 30; Digital Chart of the World-derived products), using a buffer analysis based on road networks and settlements distribution, and other parameters. Different assumptions or access thresholds should be taken into account by type of extraction practice (e.g. considering fuelwood: gatherers using vehicles, draught animals, or none of these) and by final use (e.g. selling and trade in local markets, self-consumption). For example, from a national perspective, access to areas with woody vegetation could be calculated from broad buffer zones around clusters of localities with high woodfuel consumption. When dealing with local or micro-regional accessibility patterns, more detail studies using high-resolution digital elevation models (DEMs) and local route maps are recommended. General assumptions for accessibility studies should be based on local survey data. Legal accessibility will identify the areas where wood extraction is forbidden, such as national parks or just private lands. These areas may be derived from national or international maps, such as the IUCN map of protected areas, and from cadastral databases.

The quantitative WSC value is extremely difficult to determine with precision since it depends on the capacity (potential) of an area to produce biomass which may vary widely [15]. Moreover, the majority of research on this area as noted above has concentrated on establishing the amounts of usable timber produced by commercial tree species (i.e. annual increment of stems), which is not of interest for the rural woodfuel supply [44]. On the other hand, estimating the woodfuel supply of non-forest areas is particularly complicated because of the high degree of variability in the woody cover and productivity of these areas. In many instances, the capacity of agricultural farming systems to produce woodfuels depends on the level of demand (e.g. population density [46]) and accessibility of alternative sources, which might bring their production to a higher or lower priority level, with respect to other products [22]. However, as mentioned earlier, the scope of WISDOM is not operational planning, for which quantitative precision is essential and definitely more demanding.

In this context and within the scope of identifying priority areas where the demand/supply balance indicates a possible deficit, the supply module may concentrate mainly on land use and land use change, and may use indicative biomass productivity indices based on ecological characteristics. For example, if the aim is to identify areas with potential woodfuel shortages, then the study could look for areas that show: (a) rapid depletion rates of forests and woodlands as a result of land-use changes or high pressure; (b) change in land use patterns such as increased field size and associated loss of hedges; (c) low biomass productivity; (d) poor accessibility. Alternatively, areas with larger potential for sustainable woodfuel production will be those showing accessible woody vegetation with good stocking and productivity.

3.4. *Integration module*

The main scope of the integration module is to analyze relevant interactions between the demand and supply modules in order to derive new variables that can potentially be used to prioritize areas of concern. One of the main challenges for this module is achieving a consistent integration of databases, given that demand and supply estimates come from very different sources (e.g. demand estimates are usually done by the Energy Ministry, whereas supply estimates come usually from the Forestry or Agriculture Ministries).

The integration is done through the combination of the variables related to woodfuel consumption and supply that have been systematized for each minimum administrative unit of analysis. Several variables or indicators can be designed to analyze the combined impact of woodfuel supply and demand. A necessary first step is to derive estimates of the woodfuel demand coming from different LU/LC classes. The woodfuel sources to be considered will include natural sources such as forests, other wooded lands (shrubs, shifting cultivations, etc.) and man-made sources such as forestry and agricultural plantations, agro-forestry, windbreaks, etc. Detailed information on these aspects come from local surveys, which are usually conducted over specific ecological regions, and need to be adapted to the national context using for example, wood extraction coefficients by LU/LC class.

The selection of indicators is decided case by case, depending on the availability and accuracy of the data. Potential indicators include:

- woodfuel deficit = [woodfuel supply−woodfuel demand] <0;
- potential pressure on woodfuel sources (natural and non) = [woodfuel demand/total accessible woodfuel sources];
- CO_2 net emissions = f [woodfuel deficit].

Strictly speaking, woodfuel deficit areas are those with negative values, and should include of course, demand and supply from non-forest areas. However, since it is difficult to obtain precise information on both supply and demand, different thresholds could be defined so that woodfuel deficit areas could include those with a range of values around zero.

Potential pressure on woodfuel sources is given in metric tons (t) (or cubic meters (m^3)) per hectare per year and thus gives an idea of the average local wood productivity needed to cope with the existing woodfuel demand. If the demand is higher than the wood productivity in the area, then a deficit, or unsustainable situation, may be assumed.

Net CO_2 emissions will be registered in those areas where woodfuel extraction remains unsustainable. Estimates of total Greenhouse Gases (GHG) emissions coming from woodfuels can also be derived using emission factors for the most common end-use technologies, such as open fires [47,48]. As the estimates come from a detailed spatialization of data (Fig. 2), they are much more precise than the current figures available at the National Greenhouse Inventories submitted to the United Nations Framework Convention on Climate Change (UNFCCC). The spatial analysis of woodfuel GHG emissions can also be useful for deriving regional baselines on Clean Development Mechanisms (CDM) projects.

3.5. *Identification of woodfuel hot spots*

The final step in the WISDOM approach is the identification of those areas where action is urgently needed in terms of demand, supply or both (i.e. highlighting woodfuel *hot spots*). Departing from old approaches, like the fuelwood gap model, where the identification of *hot spots* was based entirely on a quantitative estimates of woodfuel deficits, WISDOM aims at identifying areas showing a distinctive woodfuel situation and dynamics. To do so, common multivariate statistical procedures data grouping techniques, factor analysis, cluster analysis, indexing and others could be used. Alternatively, the final grouping of sub-national areas, in terms of their priority, could be done using an overall woodfuel priority index that reflects the key aspects of the areas of analysis in terms of woodfuel demand, supply and integration variables [30].

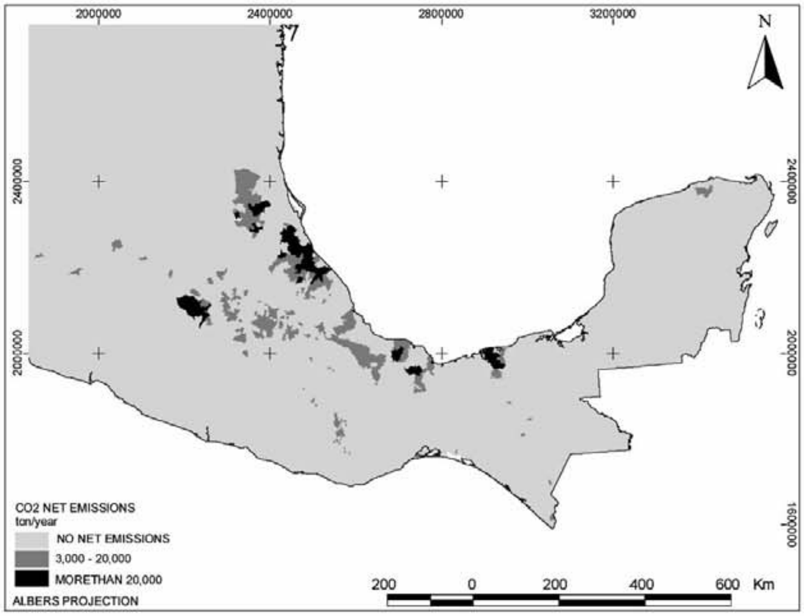


Fig. 2. CO_2 net emissions from fuelwood use in Mexico, 2000. *Notes*: The map shows the net CO_2 emissions (in metric tons (t) of CO_2 per year) by county aggregated into three categories. CO_2 net emissions are estimated as the difference fuelwood consumption and accessible woodfuel productivity of forests. This analysis shows that only in very specific regions of Mexico fuelwood harvesting is actually contributing to net CO_2 emissions to the atmosphere.

One proposed procedure for constructing the woodfuel priority index involves four sub-steps (next section provides examples of priority indexing using the WISDOM approach): (a) Selection of a robust set of variables associated with woodfuel consumption and supply, extracted from the demand, supply and/or integration modules. The selection of final set of variables needs to consider the integration of different concerns regarding woodfuel consumption and availability of resources. (b) Allocating each spatial unit of analysis to a category in terms of each of the individual variables selected in the previous step (a). (c) Construction of an integrated woodfuel priority index by unit of analysis: based on the ranking of each spatial unit of analysis for each of the variables selected. The construction of an integrated index may need multi-criteria analysis, particularly when trying to integrate variables from different fields (e.g. social/economic/environmental, qualitative/quantitative). (d) Allocating each spatial unit of analysis to a particular group according to the integrated woodfuel priority index calculated in the sub-step (c). This final step involves a re-grouping of administrative units into categories (from low priority to high priority), along the integrated woodfuel priority index.

According to a pre-defined set of criteria, WISDOM helps in rating the units of analysis, at any one scale, into priority categories. Further ratings can be conducted through successive scales of analysis (i.e. over different sets of units of analysis state, county, community, etc.). For example, if the identification of areas with potentially large social impacts is important at the national level (e.g. health problems associated to indoor air pollution), zoning can be done according to the number and density of woodfuel users, the availability of alternative fuel sources, and the socio-economic situation of woodfuel users. Studies looking at potential forest or land degradation caused by woodfuels, will try to identify regions where woodfuel consumption is high, resilient, and increasing. They will also look at cases where woodfuel supply is at risk, due to loss or degradation of natural vegetation and where the demand/supply balances indicates a deficit or where a deficit is likely to develop in the near future.

4. WISDOM case studies

So far, three case studies have been conducted using the WISDOM approach. These case studies are all at the country level and involve Mexico, Slovenia, and Senegal. They represent contrasting situations in terms of overall woodfuel dynamics, ecological and socio-economic contexts and policy implications. In this section, we present a short discussion of the most relevant features and findings for each case study; more detailed information regarding the methods used and the results obtained is available on the respective publications (Mexico [30]; Slovenia [31]; Senegal [32]).

4.1. Mexico case study

In Mexico, approximately one fourth of the population cooks with fuelwood, either alone or in combination with LPG [49,50]. The residential fuelwood demand for the year 2000 was 320 PJ [51], equivalent to 32 hm^3 of wood, a volume three times higher to the total commercial timber legally harvested in the country per year [52] (Fig. 3). Fuelwood 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. Fuelwood use in Mexico responds 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, and (d) a very diverse array of extraction practices (oak re-growth management, abandoned crop-plots management, selective extraction, random extraction, etc.). Fuelwood in Mexico is mostly collected or bought from local markets. Although diverse sources of fuelwood 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 [26,53]. Preferred species for fuelwood are not necessary the same as those of commercial value [51,53,54]. 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) [44].

The WISDOM case study conducted in Mexico [30] was directed to determine fuelwood *hot spots* for the year 2000 (Table 3). The analysis was based in the integration of national geo-referenced multi-temporal databases that cover comprehensive information on fuelwood associated variables, for 2401 municipalities or counties (out of a country total of 2436). The main data sources were (a) the last National Forest Inventory [55], with 69 land-use land-cover classes (1:250,000); (b) an extensive review of the literature and case studies in order to estimate fuelwood productivities by LU/LC class, and per capita fuelwood use by macro-ecological zone; and (c) the National Population Censuses for the years 1990 and 2000, in which data about number and distribution of fuelwood users is available. At the national level, municipalities were ranked based on (a) the number of fuelwood users; (b) the percentage of households that use fuelwood; (c) the density and (d) growth of fuelwood users; (e) the cultural resilience of fuelwood consumption (i.e. percentage of ethnic population), and (f) the magnitude of woodfuel forest resources.

The WISDOM analysis confirmed the high heterogeneity of fuelwood situations within Mexico, allowing the identification of 267 high-priority municipalities, distributed over 16 *hot spots*, where action to assure the sustainability of fuelwood use is urgently needed (Fig. 4).

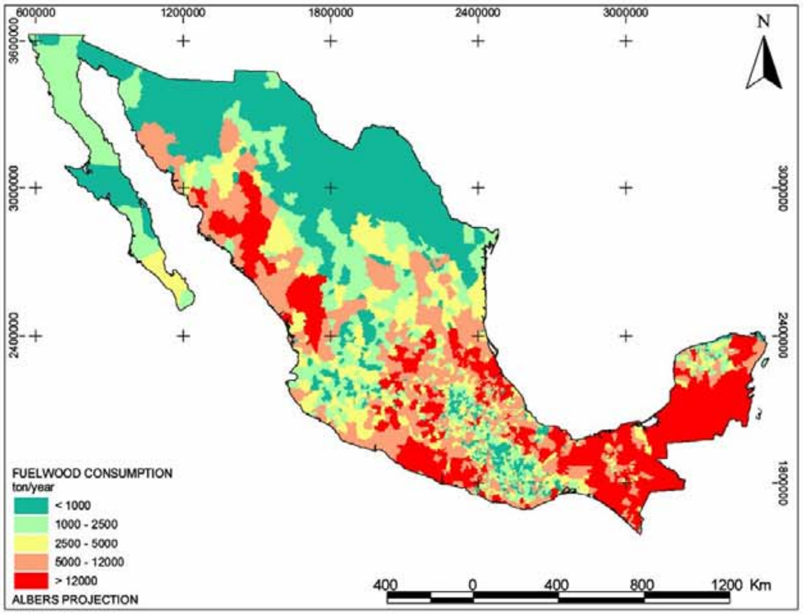


Fig. 3. Household fuelwood consumption in Mexico, 2000. *Notes*: The map shows the estimated average fuelwood consumption by municipality (county), according to number of fuelwood users and per capita consumption by major ecological zone. Counties with $>12\,kt\,yr^{-1}$ are those that deserve particular attention given their high fuelwood consumption.

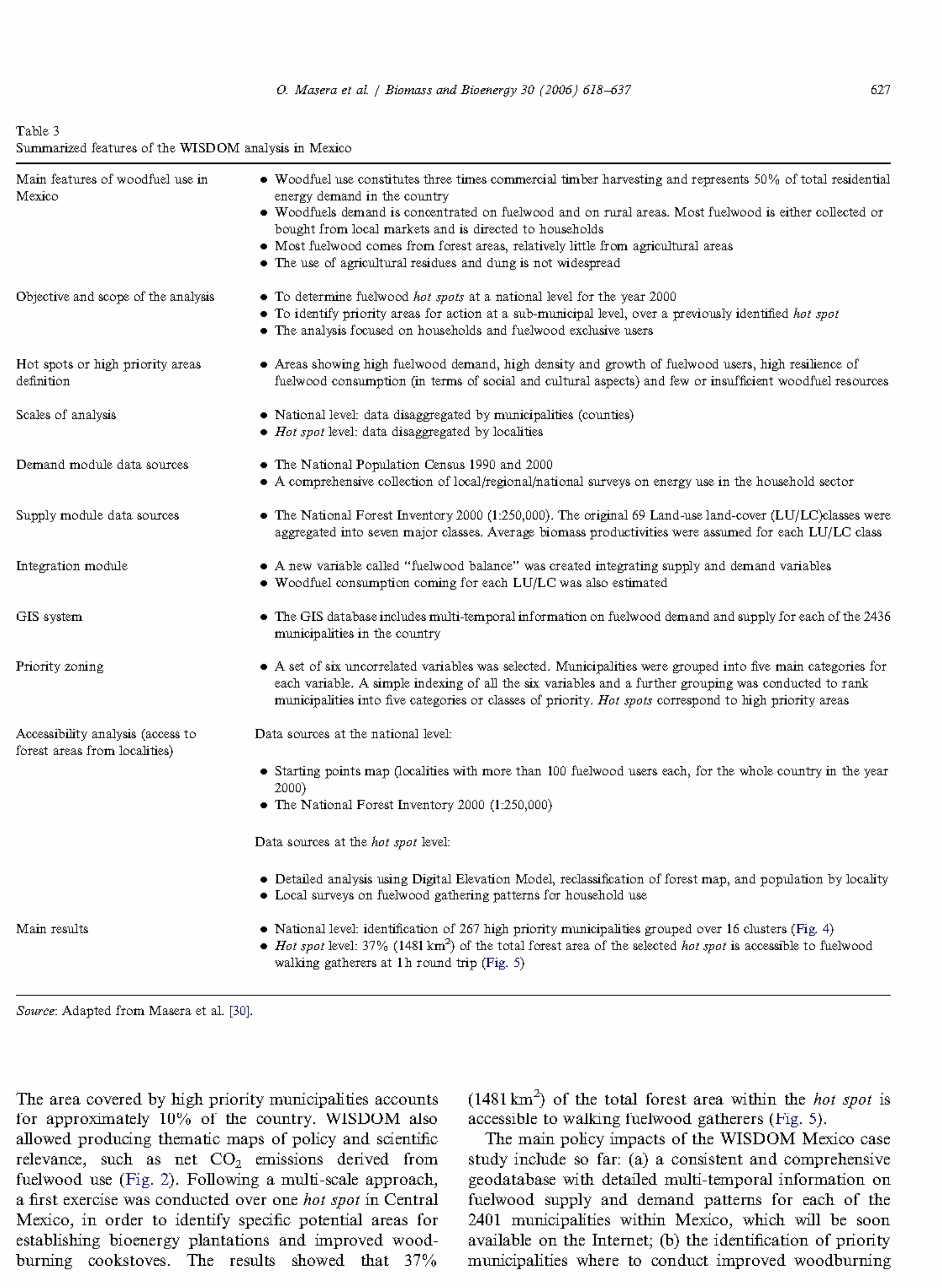


Table 3
Summarized features of the WISDOM analysis in Mexico

Main features of woodfuel use in Mexico	• Woodfuel use constitutes three times commercial timber harvesting and represents 50% of total residential energy demand in the country • Woodfuels demand is concentrated on fuelwood and on rural areas. Most fuelwood is either collected or bought from local markets and is directed to households • Most fuelwood comes from forest areas, relatively little from agricultural areas • The use of agricultural residues and dung is not widespread
Objective and scope of the analysis	• To determine fuelwood *hot spots* at a national level for the year 2000 • To identify priority areas for action at a sub-municipal level, over a previously identified *hot spot* • The analysis focused on households and fuelwood exclusive users
Hot spots or high priority areas definition	• Areas showing high fuelwood demand, high density and growth of fuelwood users, high resilience of fuelwood consumption (in terms of social and cultural aspects) and few or insufficient woodfuel resources
Scales of analysis	• National level: data disaggregated by municipalities (counties) • *Hot spot* level: data disaggregated by localities
Demand module data sources	• The National Population Census 1990 and 2000 • A comprehensive collection of local/regional/national surveys on energy use in the household sector
Supply module data sources	• The National Forest Inventory 2000 (1:250,000). The original 69 Land-use land-cover (LU/LC)classes were aggregated into seven major classes. Average biomass productivities were assumed for each LU/LC class
Integration module	• A new variable called "fuelwood balance" was created integrating supply and demand variables • Woodfuel consumption coming for each LU/LC was also estimated
GIS system	• The GIS database includes multi-temporal information on fuelwood demand and supply for each of the 2436 municipalities in the country
Priority zoning	• A set of six uncorrelated variables was selected. Municipalities were grouped into five main categories for each variable. A simple indexing of all the six variables and a further grouping was conducted to rank municipalities into five categories or classes of priority. *Hot spots* correspond to high priority areas
Accessibility analysis (access to forest areas from localities)	Data sources at the national level: • Starting points map (localities with more than 100 fuelwood users each, for the whole country in the year 2000) • The National Forest Inventory 2000 (1:250,000) Data sources at the *hot spot* level: • Detailed analysis using Digital Elevation Model, reclassification of forest map, and population by locality • Local surveys on fuelwood gathering patterns for household use
Main results	• National level: identification of 267 high priority municipalities grouped over 16 clusters (Fig. 4) • *Hot spot* level: 37% (1481 km^2) of the total forest area of the selected *hot spot* is accessible to fuelwood walking gatherers at 1 h round trip (Fig. 5)

Source: Adapted from Masera et al. [30].

The area covered by high priority municipalities accounts for approximately 10% of the country. WISDOM also allowed producing thematic maps of policy and scientific relevance, such as net CO_2 emissions derived from fuelwood use (Fig. 2). Following a multi-scale approach, a first exercise was conducted over one *hot spot* in Central Mexico, in order to identify specific potential areas for establishing bioenergy plantations and improved woodburning cookstoves. The results showed that 37% (1481 km^2) of the total forest area within the *hot spot* is accessible to walking fuelwood gatherers (Fig. 5).

The main policy impacts of the WISDOM Mexico case study include so far: (a) a consistent and comprehensive geodatabase with detailed multi-temporal information on fuelwood supply and demand patterns for each of the 2401 municipalities within Mexico, which will be soon available on the Internet; (b) the identification of priority municipalities where to conduct improved woodburning

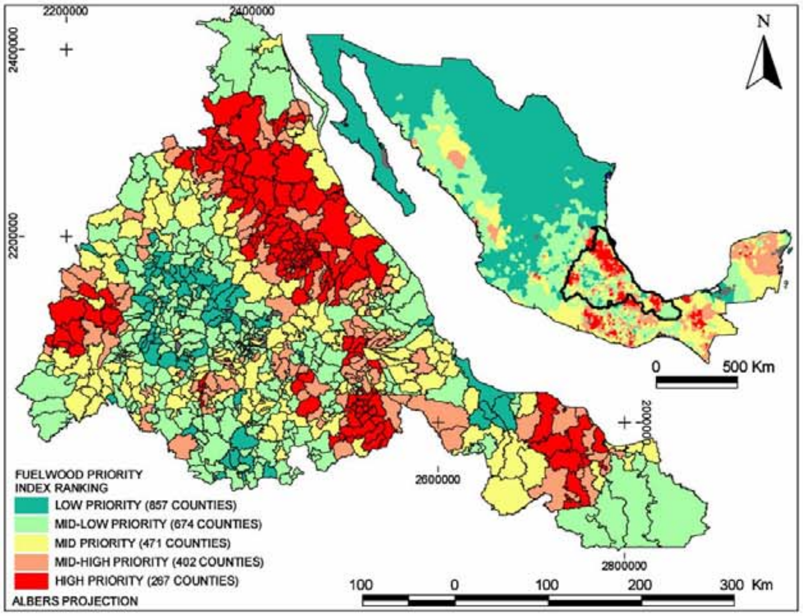


Fig. 4. Fuelwood *hot spots* in Mexico, 2000. *Notes*: (A) *Hot spots* correspond to clusters of high priority municipalities (counties in red). Priorization of counties was made using a Fuelwood Priority Index (FPI). The FPI was constructed using six variables: (a) number of fuelwood users; (b) percentage of households that use fuelwood; (c) density of fuelwood users; (d) growth of fuelwood users; (e) cultural resilience of fuelwood consumption (i.e. percentage of population belonging to indigenous groups), and (f) balance between demand and supply of fuelwood. (B) Detail for central Mexico showing the States of Estado de Mexico, Veracruz, Morelos, Hidalgo and Puebla. It can readily be seen that most *hot spots* are located in central and southern Mexico, and that they follow specific patterns, rather than being uniformly distributed over the country area.

cookstove programs and multi-purpose energy plantations, to be undertaken by the National Forestry Commission; and (c) a revision of previous GHG emission estimates coming from woodfuel burning, that has served to update and improve the Mexican National GHG Emission Inventory.

Before the WISDOM analysis was conducted, Mexican data about fuelwood consumption and supply belonged to the forestry, energy and census agencies separately. The information was neither integrated together nor shown in a spatially explicit way. WISDOM results allowed a new perspective about fuelwood use patterns in Mexico, not only because of the integration and processing of all related fuelwood data into single data sets, but because of the possibility to select specific areas of interest, according to certain criteria (i.e. fuelwood consumption, CO_2 emissions, and fuelwood priority areas).

4.2. *Slovenia case study*

Slovenia is a biomass rich country. Forests cover approximately 60% of the country and are accompanied by other land uses which are often rich of woody biomass and by consistent areas of abandoned farmland which revert to forest. The demand for woodfuels is concentrated on fuelwood (the production and use of charcoal being marginal) and on rural areas. A large part of the fuelwood trade is informal as wood is either collected by farmers from their own lands and forests or bought locally. There is a consistent wood processing industry composed of numerous small and medium units. The proportion of fuelwood coming from non-forest areas is larger than 20%. Most demand comes from households for heating purposes. Other uses such as district heating and combined heat and power plants (CHP) are still marginal but may grow as viable energy policy alternatives.

In spite of an increased interest on biomass resources and on their role as renewable energy sources, biomass goes largely unrecorded in both forestry and energy sectors and official statistics provide only generic and contradictory information. In addition, the geopolitical transformations of the last decade opened up new forest management issues related primarily to the marked fragmentation of forest ownership.

In this context, the Slovenia Forest Service (SFS) requested FAO assistance to conduct a WISDOM analysis in the country. The project's overall objective was increasing Slovenia's capacity to formulate adequate wood energy policies and plans compatible with the sustainable management of forests (Table 4). Specifically, WISDOM

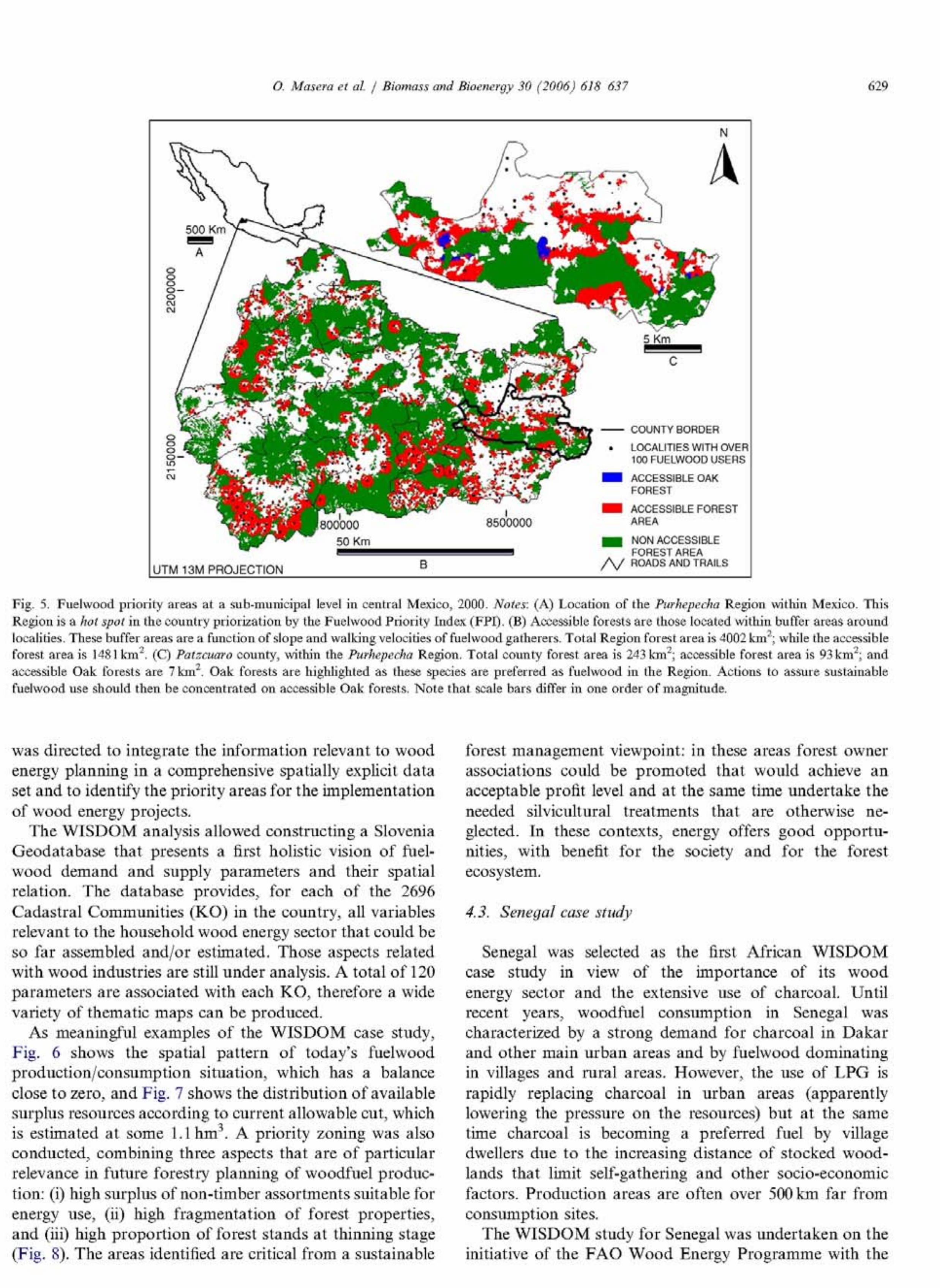


Fig. 5. Fuelwood priority areas at a sub-municipal level in central Mexico, 2000. *Notes*: (A) Location of the *Purhepecha* Region within Mexico. This Region is a *hot spot* in the country priorization by the Fuelwood Priority Index (FPI). (B) Accessible forests are those located within buffer areas around localities. These buffer areas are a function of slope and walking velocities of fuelwood gatherers. Total Region forest area is 4002 km^2; while the accessible forest area is 1481 km^2. (C) *Patzcuaro* county, within the *Purhepecha* Region. Total county forest area is 243 km^2; accessible forest area is 93 km^2; and accessible Oak forests are 7 km^2. Oak forests are highlighted as these species are preferred as fuelwood in the Region. Actions to assure sustainable fuelwood use should then be concentrated on accessible Oak forests. Note that scale bars differ in one order of magnitude.

was directed to integrate the information relevant to wood energy planning in a comprehensive spatially explicit data set and to identify the priority areas for the implementation of wood energy projects.

The WISDOM analysis allowed constructing a Slovenia Geodatabase that presents a first holistic vision of fuelwood demand and supply parameters and their spatial relation. The database provides, for each of the 2696 Cadastral Communities (KO) in the country, all variables relevant to the household wood energy sector that could be so far assembled and/or estimated. Those aspects related with wood industries are still under analysis. A total of 120 parameters are associated with each KO, therefore a wide variety of thematic maps can be produced.

As meaningful examples of the WISDOM case study, Fig. 6 shows the spatial pattern of today's fuelwood production/consumption situation, which has a balance close to zero, and Fig. 7 shows the distribution of available surplus resources according to current allowable cut, which is estimated at some 1.1 hm^3. A priority zoning was also conducted, combining three aspects that are of particular relevance in future forestry planning of woodfuel production: (i) high surplus of non-timber assortments suitable for energy use, (ii) high fragmentation of forest properties, and (iii) high proportion of forest stands at thinning stage (Fig. 8). The areas identified are critical from a sustainable forest management viewpoint: in these areas forest owner associations could be promoted that would achieve an acceptable profit level and at the same time undertake the needed silvicultural treatments that are otherwise neglected. In these contexts, energy offers good opportunities, with benefit for the society and for the forest ecosystem.

4.3. Senegal case study

Senegal was selected as the first African WISDOM case study in view of the importance of its wood energy sector and the extensive use of charcoal. Until recent years, woodfuel consumption in Senegal was characterized by a strong demand for charcoal in Dakar and other main urban areas and by fuelwood dominating in villages and rural areas. However, the use of LPG is rapidly replacing charcoal in urban areas (apparently lowering the pressure on the resources) but at the same time charcoal is becoming a preferred fuel by village dwellers due to the increasing distance of stocked woodlands that limit self-gathering and other socio-economic factors. Production areas are often over 500 km far from consumption sites.

The WISDOM study for Senegal was undertaken on the initiative of the FAO Wood Energy Programme with the

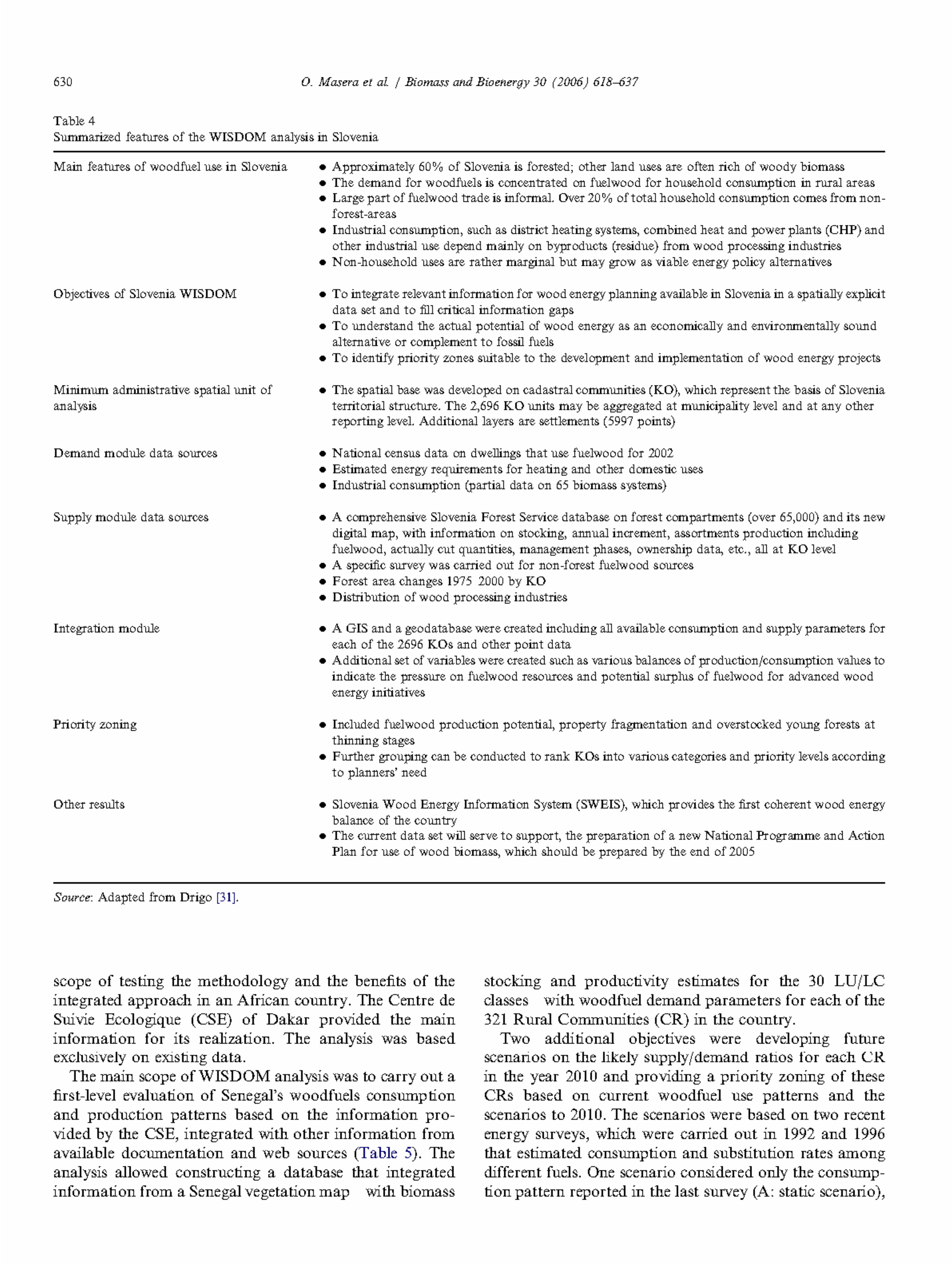


Table 4
Summarized features of the WISDOM analysis in Slovenia

Main features of woodfuel use in Slovenia	● Approximately 60% of Slovenia is forested; other land uses are often rich of woody biomass ● The demand for woodfuels is concentrated on fuelwood for household consumption in rural areas ● Large part of fuelwood trade is informal. Over 20% of total household consumption comes from non-forest-areas ● Industrial consumption, such as district heating systems, combined heat and power plants (CHP) and other industrial use depend mainly on byproducts (residue) from wood processing industries ● Non-household uses are rather marginal but may grow as viable energy policy alternatives
Objectives of Slovenia WISDOM	● To integrate relevant information for wood energy planning available in Slovenia in a spatially explicit data set and to fill critical information gaps ● To understand the actual potential of wood energy as an economically and environmentally sound alternative or complement to fossil fuels ● To identify priority zones suitable to the development and implementation of wood energy projects
Minimum administrative spatial unit of analysis	● The spatial base was developed on cadastral communities (KO), which represent the basis of Slovenia territorial structure. The 2,696 KO units may be aggregated at municipality level and at any other reporting level. Additional layers are settlements (5997 points)
Demand module data sources	● National census data on dwellings that use fuelwood for 2002 ● Estimated energy requirements for heating and other domestic uses ● Industrial consumption (partial data on 65 biomass systems)
Supply module data sources	● A comprehensive Slovenia Forest Service database on forest compartments (over 65,000) and its new digital map, with information on stocking, annual increment, assortments production including fuelwood, actually cut quantities, management phases, ownership data, etc., all at KO level ● A specific survey was carried out for non-forest fuelwood sources ● Forest area changes 1975 2000 by KO ● Distribution of wood processing industries
Integration module	● A GIS and a geodatabase were created including all available consumption and supply parameters for each of the 2696 KOs and other point data ● Additional set of variables were created such as various balances of production/consumption values to indicate the pressure on fuelwood resources and potential surplus of fuelwood for advanced wood energy initiatives
Priority zoning	● Included fuelwood production potential, property fragmentation and overstocked young forests at thinning stages ● Further grouping can be conducted to rank KOs into various categories and priority levels according to planners' need
Other results	● Slovenia Wood Energy Information System (SWEIS), which provides the first coherent wood energy balance of the country ● The current data set will serve to support, the preparation of a new National Programme and Action Plan for use of wood biomass, which should be prepared by the end of 2005

Source: Adapted from Drigo [31].

scope of testing the methodology and the benefits of the integrated approach in an African country. The Centre de Suivie Ecologique (CSE) of Dakar provided the main information for its realization. The analysis was based exclusively on existing data.

The main scope of WISDOM analysis was to carry out a first-level evaluation of Senegal's woodfuels consumption and production patterns based on the information provided by the CSE, integrated with other information from available documentation and web sources (Table 5). The analysis allowed constructing a database that integrated information from a Senegal vegetation map with biomass stocking and productivity estimates for the 30 LU/LC classes with woodfuel demand parameters for each of the 321 Rural Communities (CR) in the country.

Two additional objectives were developing future scenarios on the likely supply/demand ratios for each CR in the year 2010 and providing a priority zoning of these CRs based on current woodfuel use patterns and the scenarios to 2010. The scenarios were based on two recent energy surveys, which were carried out in 1992 and 1996 that estimated consumption and substitution rates among different fuels. One scenario considered only the consumption pattern reported in the last survey (A: static scenario), *O. Masera et al. / Biomass and Bioenergy 30 (2006) 618–637* 631

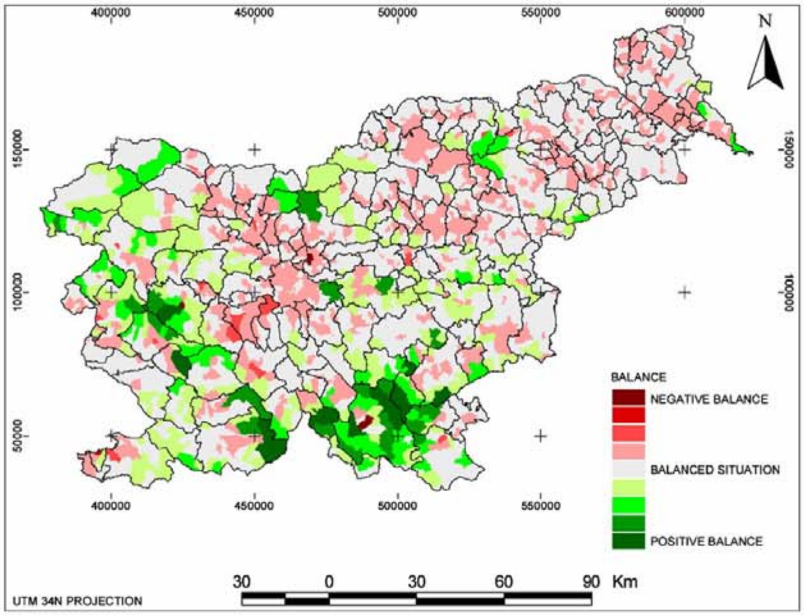


Fig. 6. Current fuelwood balance in Slovenia, 2002. *Notes*: The map shows the spatial pattern of current fuelwood balance between production and consumption. The balance is defined as the difference between the estimated fuelwood actually extracted from Slovenia forests and non-forest areas and fuelwood consumption for domestic heating and cooking.

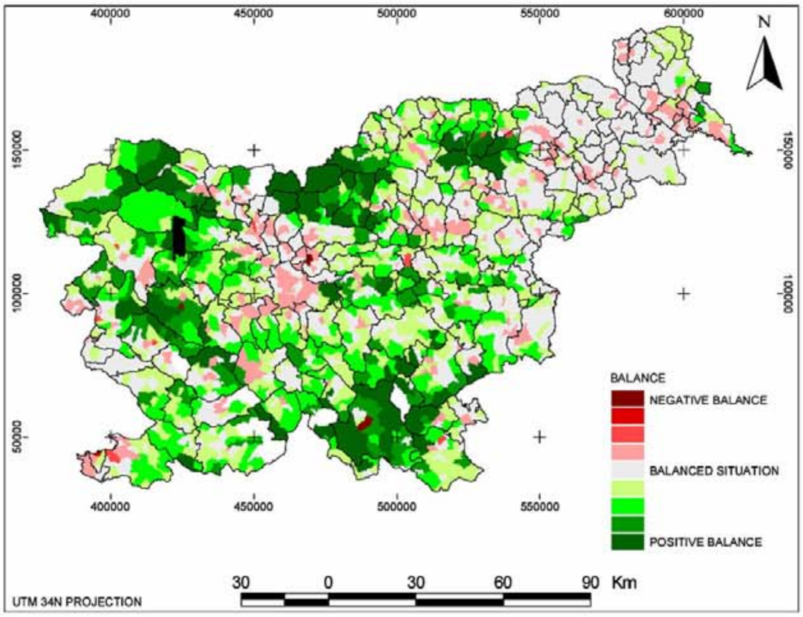


Fig. 7. Potential fuelwood balance in Slovenia, 2002. *Notes*: The map shows the spatial pattern of potential fuelwood production/consumption balance between current non-timber allowable cut plus the estimated non-forest productivity and household consumption. Overall balance is estimated to be over 1.1 hm^3. The darker green areas indicate the locations with highest woody biomass surplus. In these areas, for instance, new wood energy systems could be located.

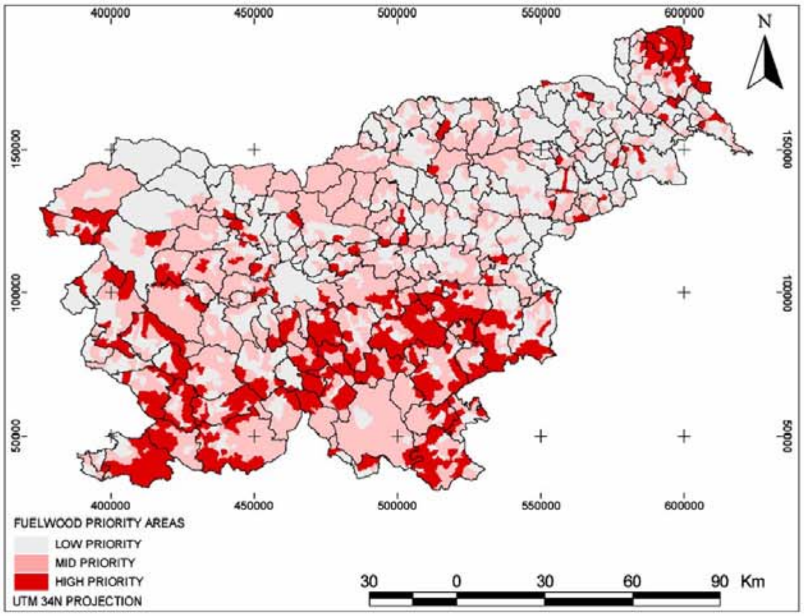


Fig. 8. Fuelwood priority areas in Slovenia, 2002. *Notes*: The map shows an example of priority zoning derived from the combination of three thematic elements: property fragmentation; wood surplus considering current local consumption and potential sustainable productivity; and fraction of forests at thinning stage. Red areas are those with higher values in the three thematic elements.

projected using population growth in rural and urban areas. The second scenario considered also the 1992 1996 fuel substitution rates (B: dynamic scenario). In this case there is a reduction of fuelwood and charcoal consumption in urban areas in favor of LPG and a significant shift from fuelwood to charcoal in rural areas, which appeared as the potentially most critical factor, setting an unprecedented strain on the country's limited wood resources. If the trends assumed in scenario B become real, one of the important effects of the changing consumption patterns is the likely spreading of charcoal production to respond to a more diffuse local demand. This may cause a sudden increase of charcoal-making in areas previously undisturbed (at least for this specific use), making the pressure on local wood resources more ubiquitous and more difficult to control and manage. Figs. 9 and 10 show, respectively, the supply/demand balance at year 2010 according to the static scenario (A) and to the "dynamic" scenario (B).

A preliminary Woodfuel Priority Index (WPI) was developed using several indices based on the possible levels of consumption at year 2010, on the consequent local supply/demand balance and on socio-economic parameters that represent the poverty level (CSE poverty index). Fig. 11 shows the result of this process, highlighting the Rural Communities that deserve particular attention in view of their combined levels of consumption and balance (according to the "dynamic" scenario) and of access to basic social services and infrastructures, defined by the CSE's poverty index.

5. Conclusions and future research directions

The WISDOM approach allows constructing an integrated and comprehensive perspective of wood energy systems that catalyzes the dialogue between forestry and energy agencies and that facilitates the definition of sound policies and strategies.

The main benefits of using WISDOM include:

- It allows a holistic vision of the wood energy sector over an entire country or region; while identifying circumscribed priority target areas, where action should be concentrated in order to optimize the use of available human, institutional, and financial resources.
- It can be used to promote the development of wood energy as a locally available and environmentally friendly source of energy.
- It helps to clarify the true role of forestry and agricultural sectors in supplying woodfuels, and it is hoped that, in doing this, it will favor a clearer allocation of responsibilities and promote synergies.
- Within the context of climate change, WISDOM is a useful tool for helping in developing National GHG Inventories.

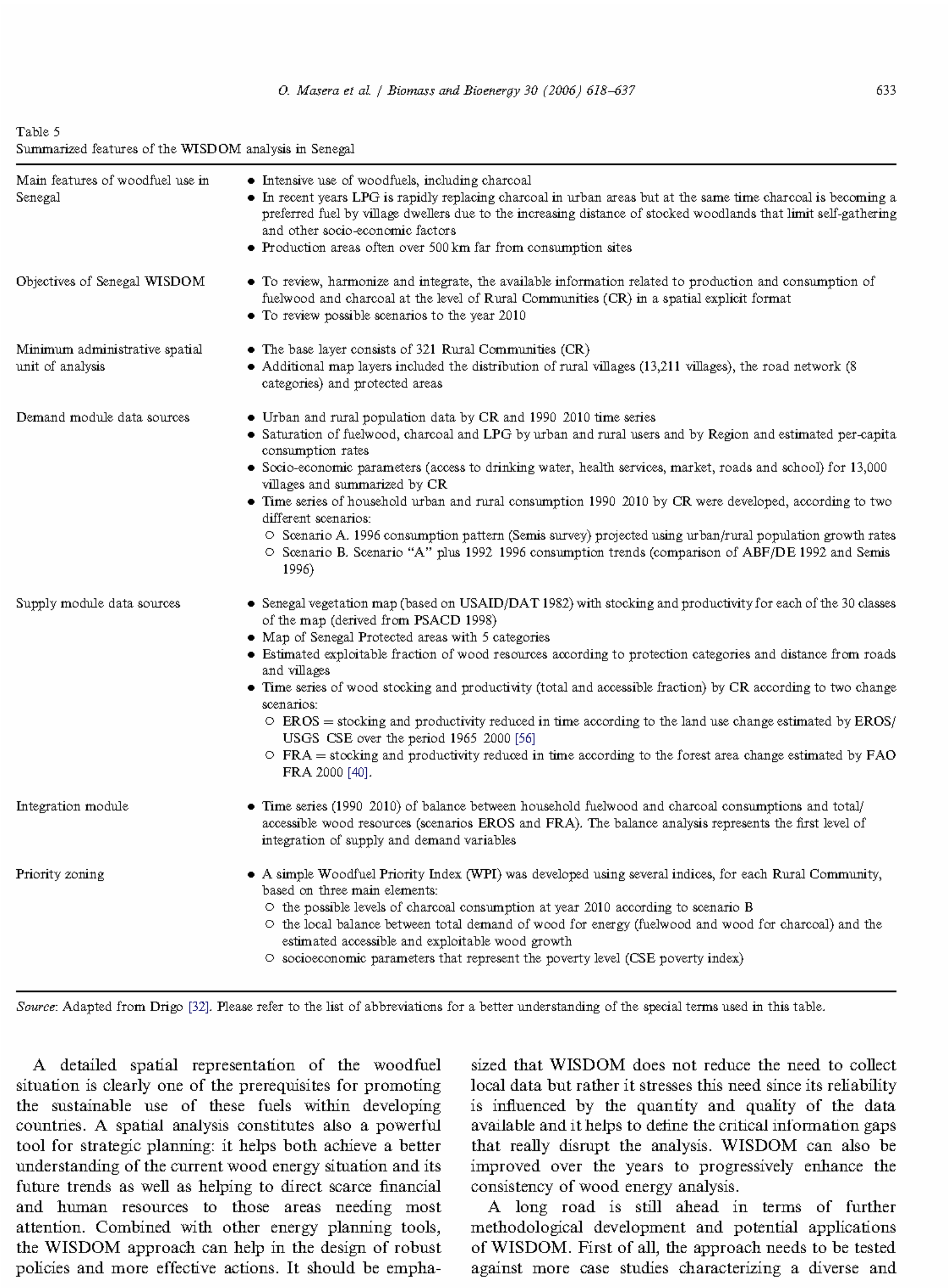


Table 5
Summarized features of the WISDOM analysis in Senegal

Main features of woodfuel use in Senegal	● Intensive use of woodfuels, including charcoal ● In recent years LPG is rapidly replacing charcoal in urban areas but at the same time charcoal is becoming a preferred fuel by village dwellers due to the increasing distance of stocked woodlands that limit self-gathering and other socio-economic factors ● Production areas often over 500 km far from consumption sites
Objectives of Senegal WISDOM	● To review, harmonize and integrate, the available information related to production and consumption of fuelwood and charcoal at the level of Rural Communities (CR) in a spatial explicit format ● To review possible scenarios to the year 2010
Minimum administrative spatial unit of analysis	● The base layer consists of 321 Rural Communities (CR) ● Additional map layers included the distribution of rural villages (13,211 villages), the road network (8 categories) and protected areas
Demand module data sources	● Urban and rural population data by CR and 1990 2010 time series ● Saturation of fuelwood, charcoal and LPG by urban and rural users and by Region and estimated per-capita consumption rates ● Socio-economic parameters (access to drinking water, health services, market, roads and school) for 13,000 villages and summarized by CR ● Time series of household urban and rural consumption 1990 2010 by CR were developed, according to two different scenarios: ○ Scenario A. 1996 consumption pattern (Semis survey) projected using urban/rural population growth rates ○ Scenario B. Scenario "A" plus 1992 1996 consumption trends (comparison of ABF/DE 1992 and Semis 1996)
Supply module data sources	● Senegal vegetation map (based on USAID/DAT 1982) with stocking and productivity for each of the 30 classes of the map (derived from PSACD 1998) ● Map of Senegal Protected areas with 5 categories ● Estimated exploitable fraction of wood resources according to protection categories and distance from roads and villages ● Time series of wood stocking and productivity (total and accessible fraction) by CR according to two change scenarios: ○ EROS = stocking and productivity reduced in time according to the land use change estimated by EROS/USGS CSE over the period 1965 2000 [56] ○ FRA = stocking and productivity reduced in time according to the forest area change estimated by FAO FRA 2000 [40].
Integration module	● Time series (1990 2010) of balance between household fuelwood and charcoal consumptions and total/accessible wood resources (scenarios EROS and FRA). The balance analysis represents the first level of integration of supply and demand variables
Priority zoning	● A simple Woodfuel Priority Index (WPI) was developed using several indices, for each Rural Community, based on three main elements: ○ the possible levels of charcoal consumption at year 2010 according to scenario B ○ the local balance between total demand of wood for energy (fuelwood and wood for charcoal) and the estimated accessible and exploitable wood growth ○ socioeconomic parameters that represent the poverty level (CSE poverty index)

Source: Adapted from Drigo [32]. Please refer to the list of abbreviations for a better understanding of the special terms used in this table.

A detailed spatial representation of the woodfuel situation is clearly one of the prerequisites for promoting the sustainable use of these fuels within developing countries. A spatial analysis constitutes also a powerful tool for strategic planning: it helps both achieve a better understanding of the current wood energy situation and its future trends as well as helping to direct scarce financial and human resources to those areas needing most attention. Combined with other energy planning tools, the WISDOM approach can help in the design of robust policies and more effective actions. It should be emphasized that WISDOM does not reduce the need to collect local data but rather it stresses this need since its reliability is influenced by the quantity and quality of the data available and it helps to define the critical information gaps that really disrupt the analysis. WISDOM can also be improved over the years to progressively enhance the consistency of wood energy analysis.

A long road is still ahead in terms of further methodological development and potential applications of WISDOM. First of all, the approach needs to be tested against more case studies characterizing a diverse and

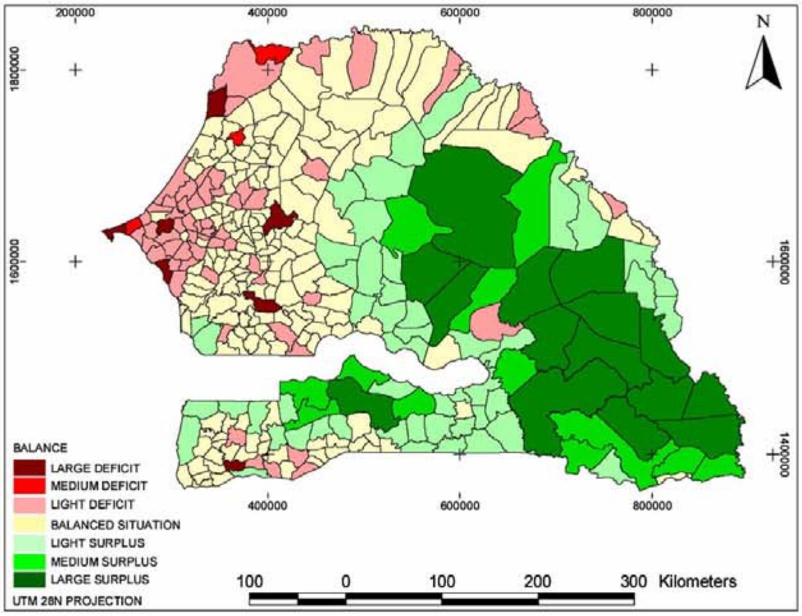


Fig. 9. Fuelwood balance scenario in Senegal for the year 2010-A. *Notes*: The map shows the balance between household woodfuel consumption (fuelwood and wood for charcoal) and estimated sustainable productivity according to the "static" scenario (A) (see text), which used the 1996 consumption survey data projected according to population growth rates in urban and rural areas.

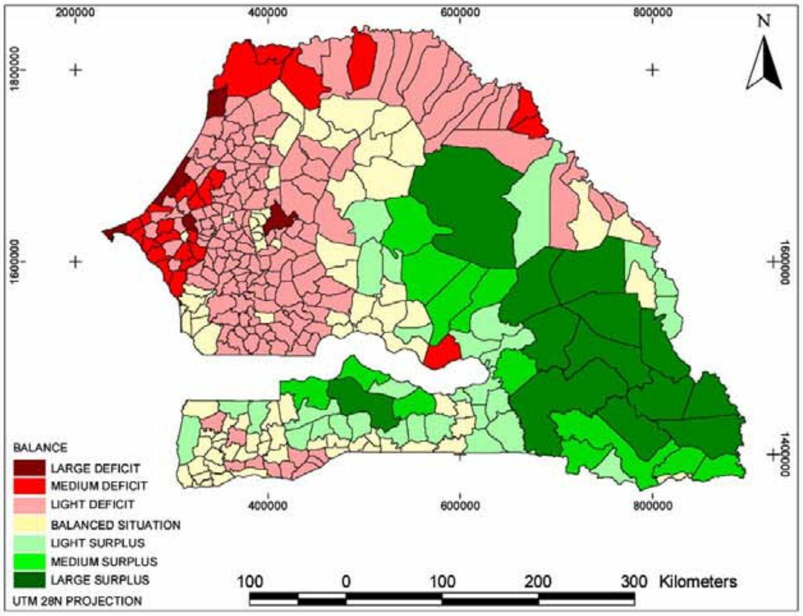


Fig. 10. Fuelwood balance scenario in Senegal for the year 2010-**B**. *Notes*: The map shows the balance between household woodfuel consumption (fuelwood and wood for charcoal) and estimated sustainable productivity according to the "dynamic" scenario (B) which used the 1996 consumption survey data but projected the consumption according to the 1992–1996 trends and to population growth rates. Also shown are the "traditional" charcoal production areas.

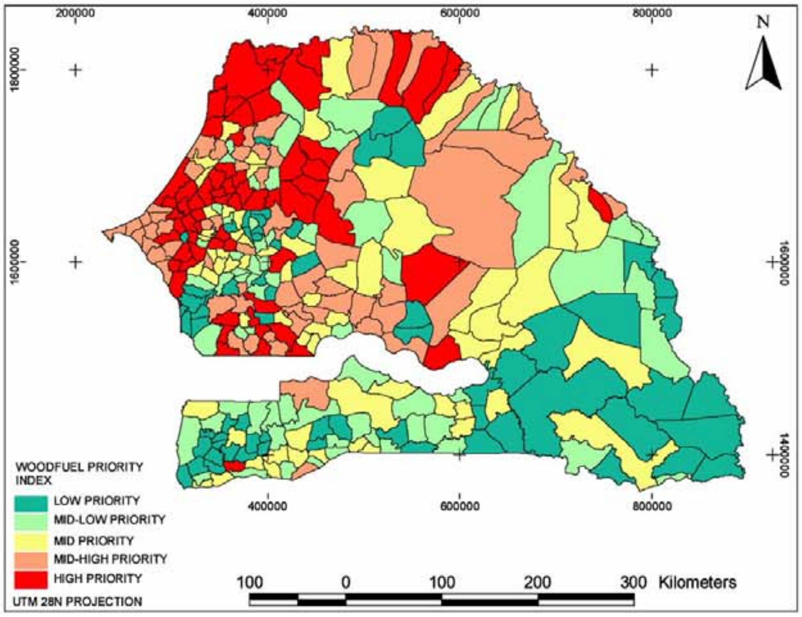


Fig. 11. Overall woodfuel priority areas in Senegal, 2010. *Notes*: The map shows the estimated woodfuel priority areas within Senegal for the year 2010. The figure highlights the Rural Communities that deserve particular attention in view of their combined levels of consumption and balance (according to scenario B in Fig. 10) and of their limited access to basic social services and infrastructures, defined by the poverty index developed by the Dakar's Centre de Suivi Ecologique (CSE), Senegal 2002.

contrasting set of circumstances. Case studies that deserve attention include situations were a large fraction of woodfuels come from agricultural areas or from non-woody biomass. The new challenges coming from these case-studies will serve to make the methodology more robust and adaptable to the variety of circumstances that may be found in different countries.

Moreover, clear linkages between the WISDOM analysis at the national/regional level and interventions at the local level must be developed. Having identified the woodfuel *hot spots* at a national/sub-national level, a more detailed spatial analysis needs to be conducted within each of the priority areas or *hot spots* [30]. For this purpose, a better understanding of the local woodfuel system (i.e. the different ways in which wood resources are produced, harvested, transformed and converted finally to energy, taking into account the larger context of forest resources) is needed. Masera et al. [30] shows an example of this type of analysis for a region in Central Mexico. The analysis of the local woodfuel system will allow the identification of concrete topics and issues for actual interventions. Thus, a logical chain of actions from national planning to local intervention can be established. It should be noted that this last step will need additional planning and implementation tools as well as a participatory approach that effectively incorporates the local population.

Acknowledgements

The authors are grateful to Margaret Skutsch, for her invaluable comments and suggestions on the first draft of the paper.

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II.2 Actualización de nuevos estudios de caso que utilizaron el modelo WISDOM

Al momento de terminar esta tesis, se ha aplicado el modelo WISDOM en tres nuevos estudios de caso alrededor del mundo. Así mismo, países como Argentina, España y Guinea Bissau han mostrado interés en el modelo. Por cualquier duda referente a la metodología y sus potenciales de aplicación, se recomienda al lector contactarse directamente con los autores de los reportes y artículos científicos citados en la presente tesis.

II.2.1 Brasil[11]

El objetivo central del estudio fue implementar el modelo WISDOM en Brasil, mediante el cual se obtuvo por primera vez una evaluación integral de los patrones espaciales de oferta y demanda de madera para energía en ese país.

Figura II.1. Mapa de coberturas del suelo de Brasil generado para el proyecto WISDOM.

Fuente: Ghilardi (2007).

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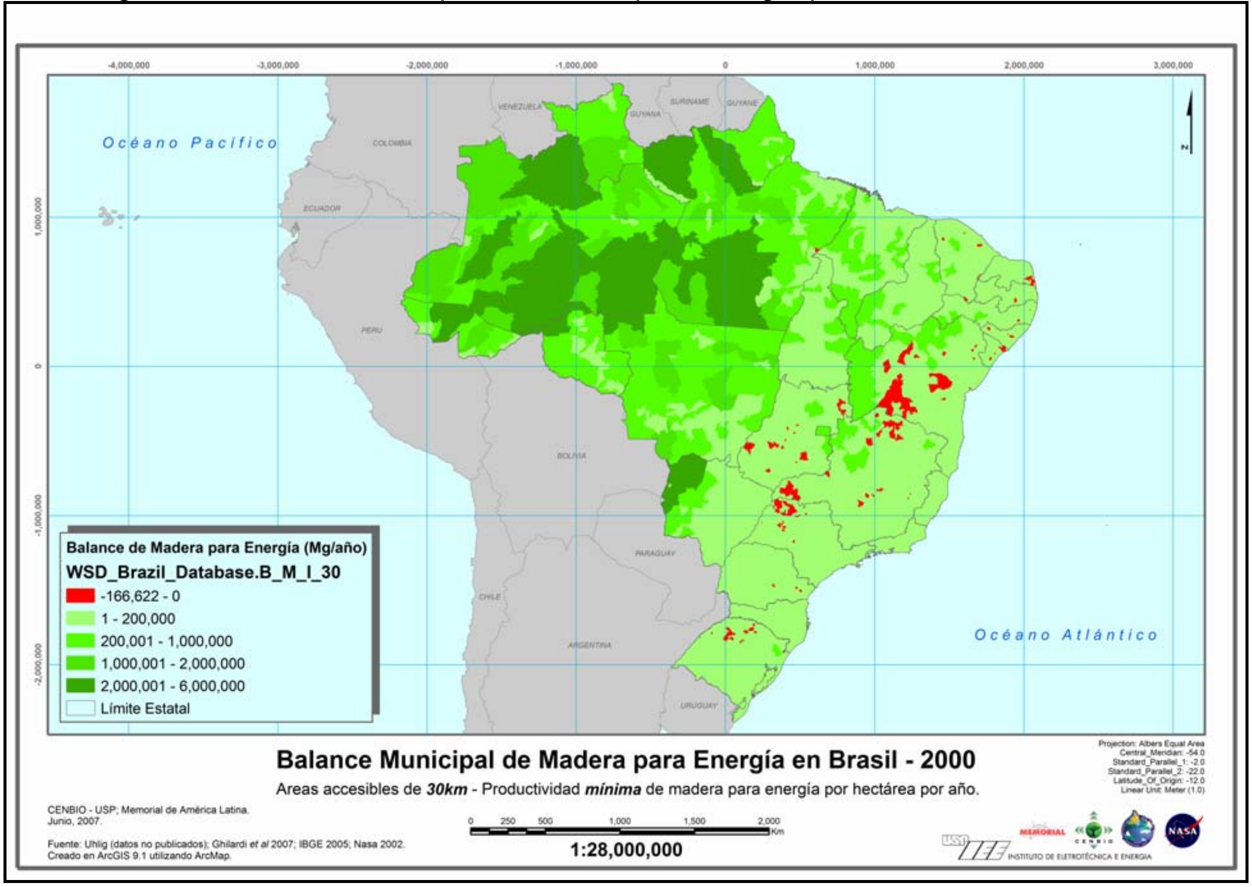
Figura II.2. Balance municipal de madera para energía para el año 2000 en Brasil.

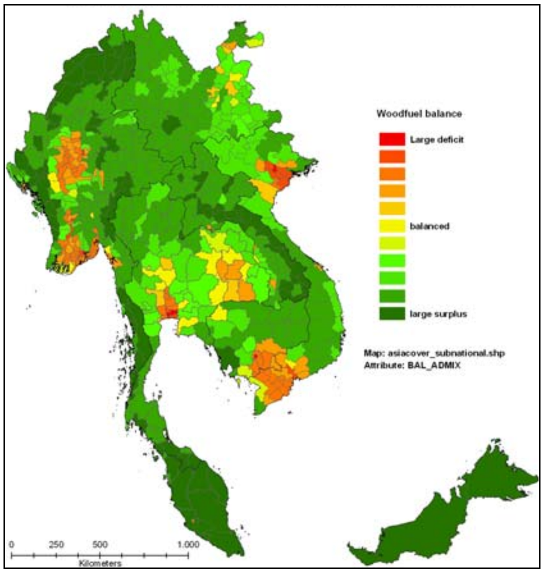


Fuente: Ghilardi (2007). Notas: Oferta natural según mapa de coberturas del suelo (a partir de datos de productividad recopilados por Ghilardi *et al.* (2007) menos la producción de madera para energía según información censal, excluyendo aquella que viene de plantaciones energéticas. Se consideraron aéreas accesibles de 30km alrededor de localidades y carreteras principales, y una productividad mínima esperada de madera para energía por hectárea por año para cada categoría de cobertura del suelo.

II.2.2 Sudeste Asiático[12]

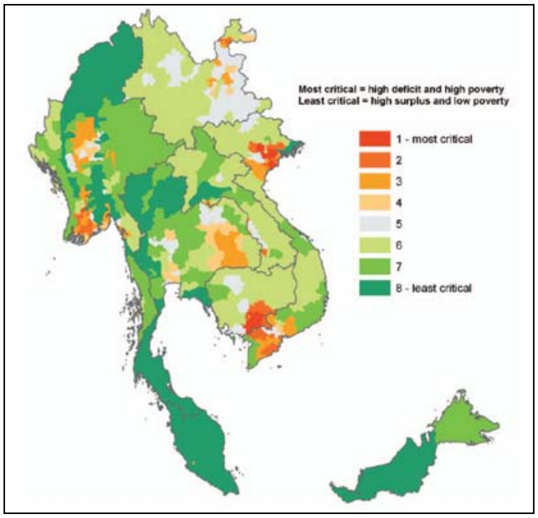
El estudio se llevó a cabo para Camboya, Laos, Malasia, Myanmar, Tailandia, Vietnam y la provincia china de Yunnan. Mediante la priorización de unidades espaciales de 81 km2 se estimó que el 14% del área total (min=0.4% en Malasia y max=27% en Vietnam) presentan situaciones deficitarias en el abasto de combustibles de madera.

Figura II.3. Relación entre oferta y demanda de combustibles de madera para el año 2000 en el Sudeste Asiático.



Fuente: Drigo (2007b). Notas: las unidades básicas de análisis espacial corresponden al nivel sub-nacional i.e. homólogas a los Estados en México.

Figura II.4. Pobreza extrema y disponibilidad de combustibles de madera para el año 2000 en el Sudeste Asiático.



Fuente: Drigo (2007b).

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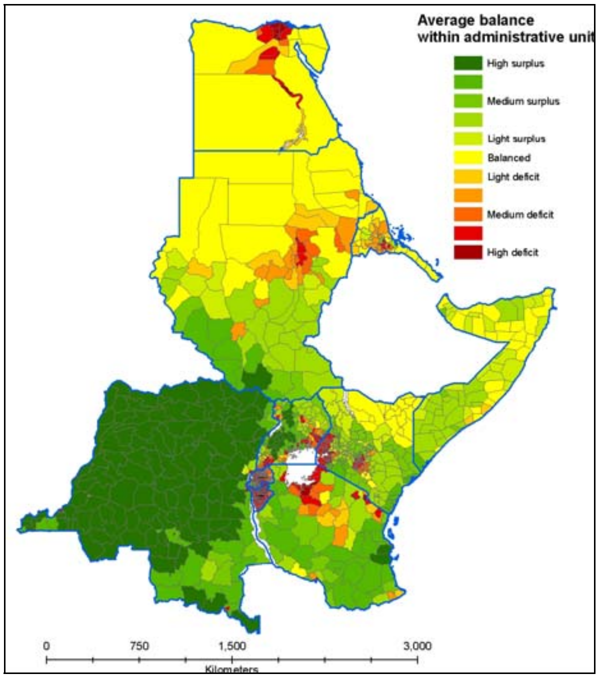
[12] Drigo, R., 2007. Wood-energy supply/demand scenarios in the context of poverty mapping. A WISDOM case study in Southeast Asia for the years 2000 and 2015. FAO Wood Energy Programme (FOPP) and Poverty Mapping Project (SDRN). Food and Agriculture Organization (FAO) of the United Nations (UN), Rome. Available on the Internet: http://www.fao.org/nr/geo/abst/geo_071101_en.htm (última visita en Abril del 2008).

II.2.3 África del Este[13]

El estudio se llevó a cabo para Rwanda, Kenia, Egipto, Burundi, Congo, Eritrea, Somalia, Sudan, Tanzania y Uganda. Las áreas que presentan situaciones deficitarias entre la oferta y la demanda de combustibles de madera equivalen al 12.5% del área total. La ocurrencia y distribución de estas áreas es muy variable entre los distintos países. Los países mayormente dominados por áreas deficitarias son Burundi y Rwanda.

Figura II.5. Relación entre oferta y demanda de combustibles de madera para el año 2000 en África del Este.



Fuente: Drigo (2007a). Notas: las unidades básicas de análisis espacial corresponden al nivel sub-nacional i.e. homólogas a los Estados en México.

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III. ANÁLISIS ESPACIAL DE LOS PATRONES DE OFERTA Y DEMANDA DE LEÑA PARA USO RESIDENCIAL EN MÉXICO UTILIZANDO EL MODELO *WISDOM*

III.1 Spatial analysis of residential fuelwood supply and demand patterns in Mexico using the WISDOM approach

A continuación se adjunta el artículo publicado en la revista *Biomass and Bioenergy*, volumen 31, año 2007.[14]

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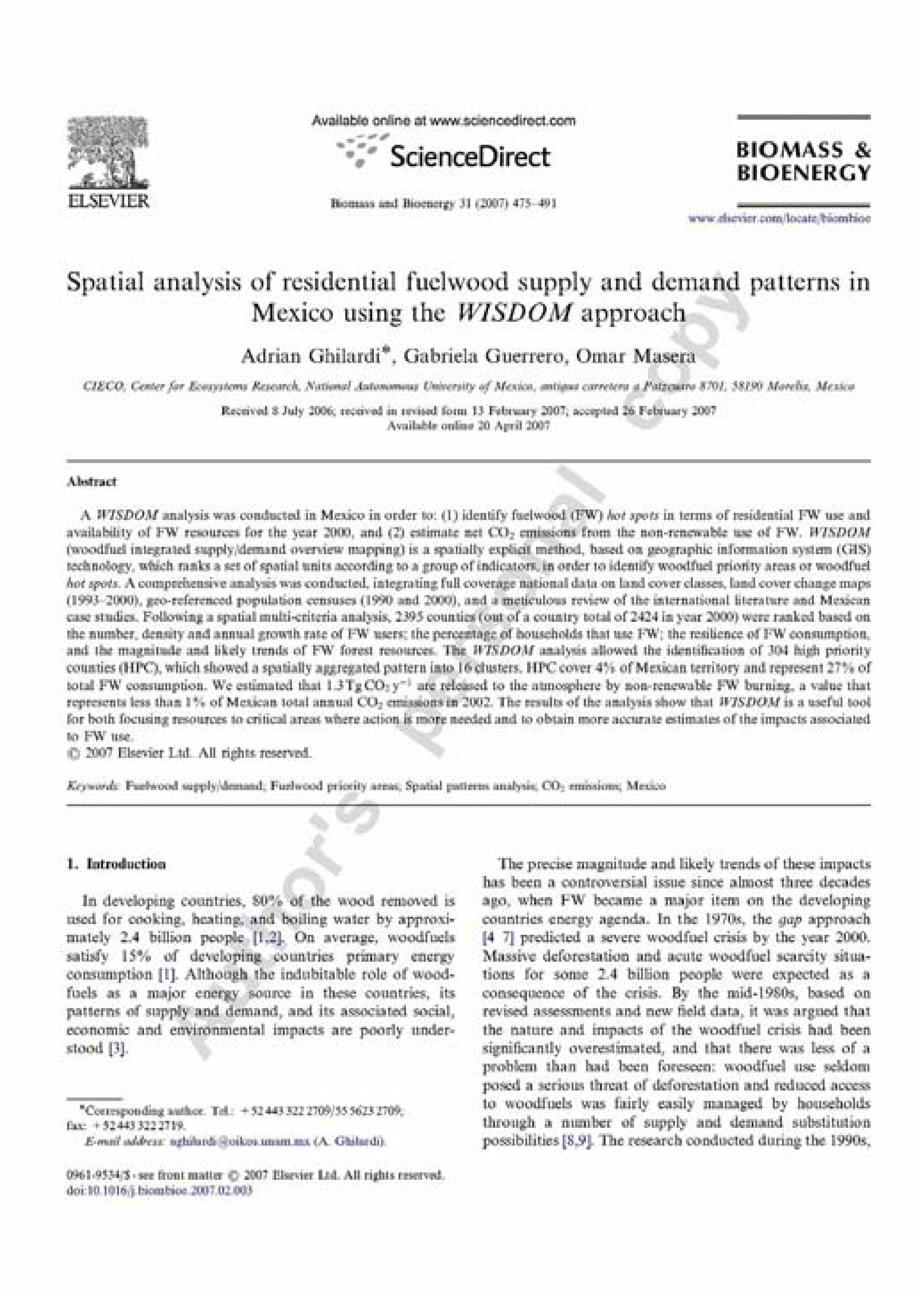
[14] Se puede obtener una copia en formato PDF del artículo desde la página Web de la revista: http://www.elsevier.com/wps/find/journaldescription.cws_home/986/description#description *"Search through the articles of this journal"*. Si no cuenta con el permiso de acceso, favor de contactarse con aghilardi@oikos.unam.mx y le será enviada una copia en formato PDF a la brevedad.



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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.

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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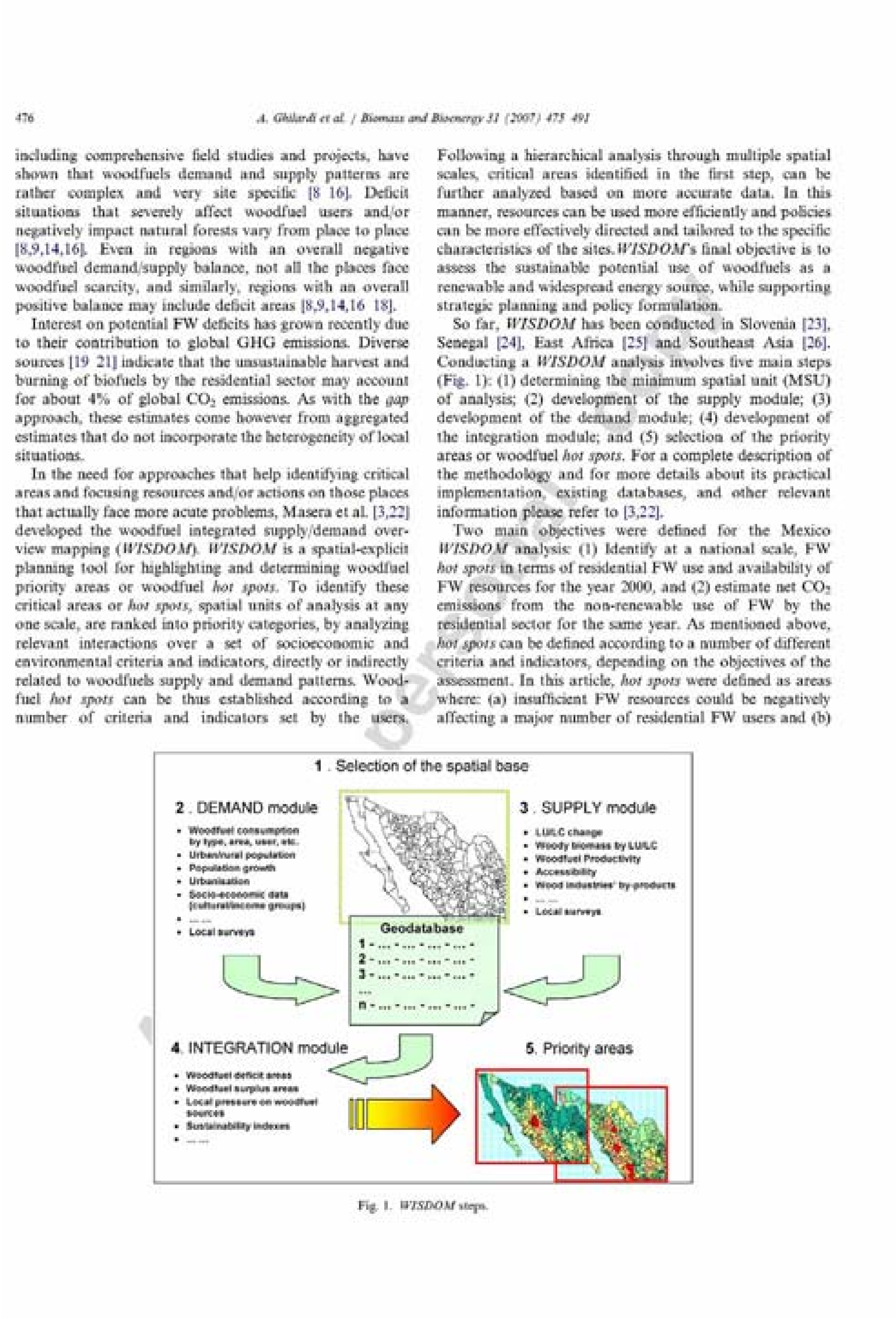


including comprehensive field studies and projects, have shown that woodfuels demand and supply patterns are rather complex and very site specific [8–16]. Deficit situations that severely affect woodfuel users and/or negatively impact natural forests vary from place to place [8,9,14,16]. Even in regions 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).

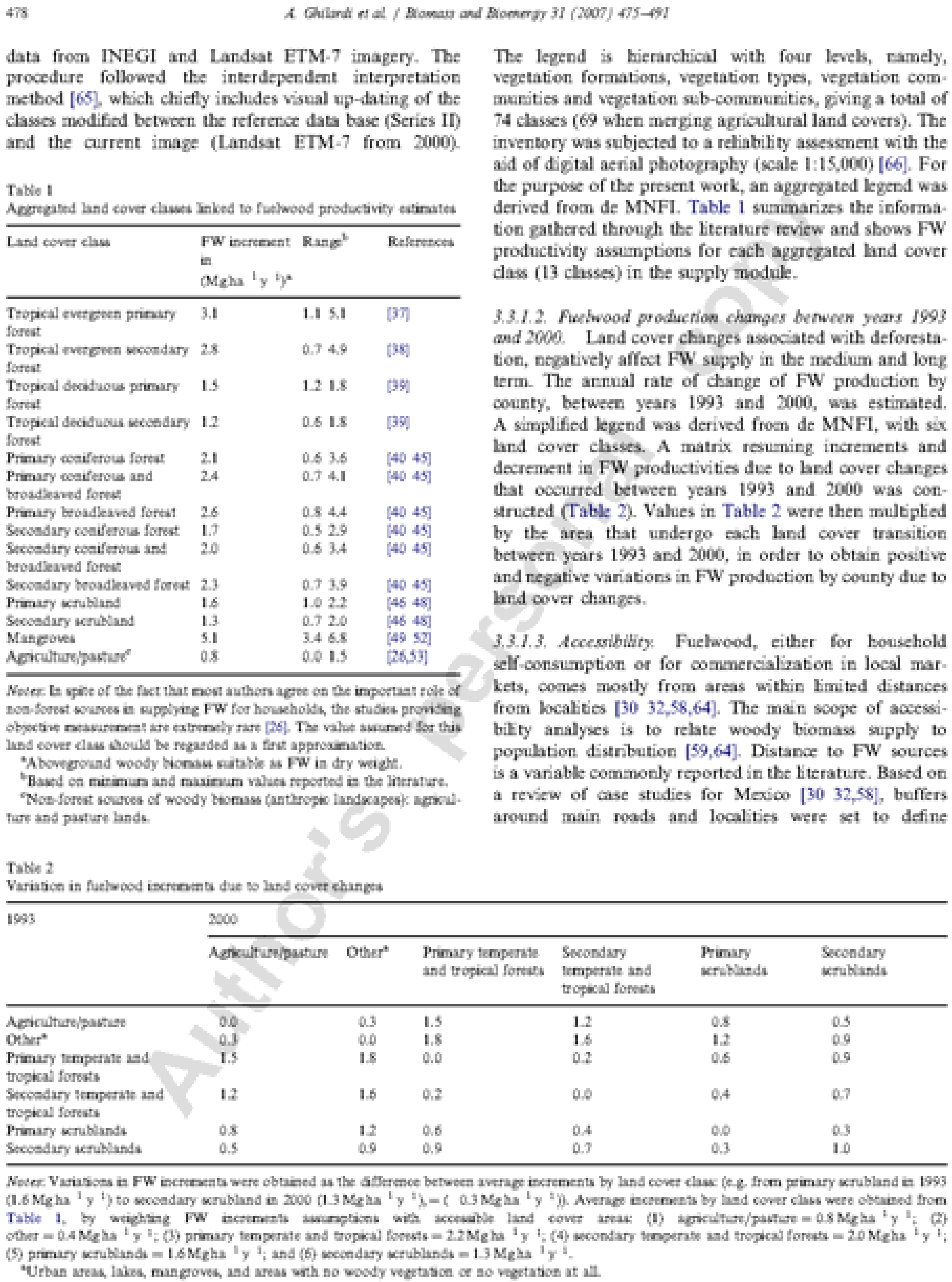
3.3. Supply module

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



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).

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.

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.

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.

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 Díaz [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 Díaz [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.

$$\lambda = (U_t/U_0)^{1/t}, \tag{6}$$

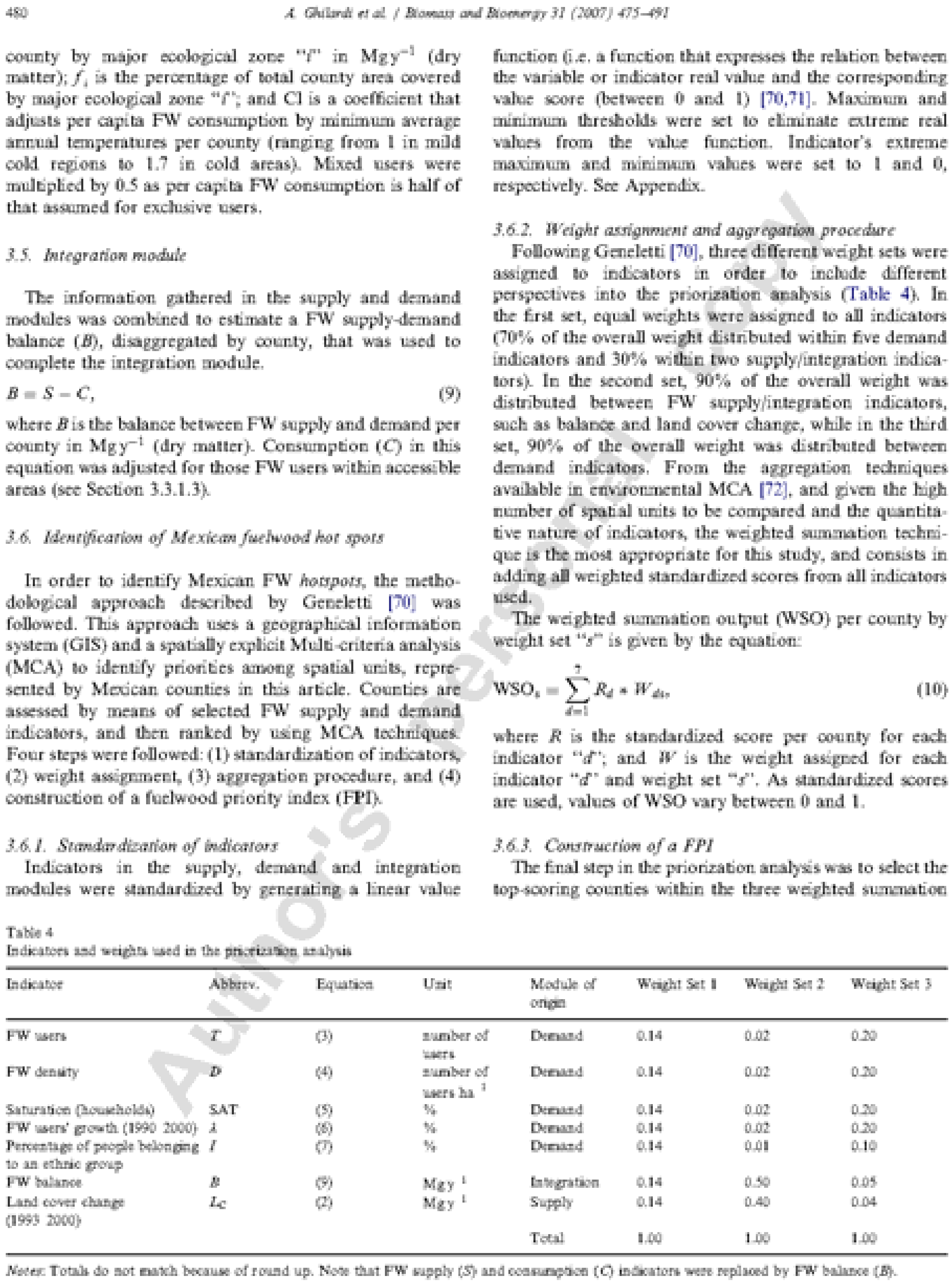
where λ is the discrete rate of FW users' growth between years 1990 and 2000 per county; U_t are FW users per county in year 2000; U_0 are FW users per county in year 1990 and t is 10 years.

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

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.

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

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



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 CI 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).

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, SAT, A and I), will not be ranked as top scoring as the WSO_3, 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 (WSO_k). 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 Díaz [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 Díaz [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 $B \geq 0$; 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,

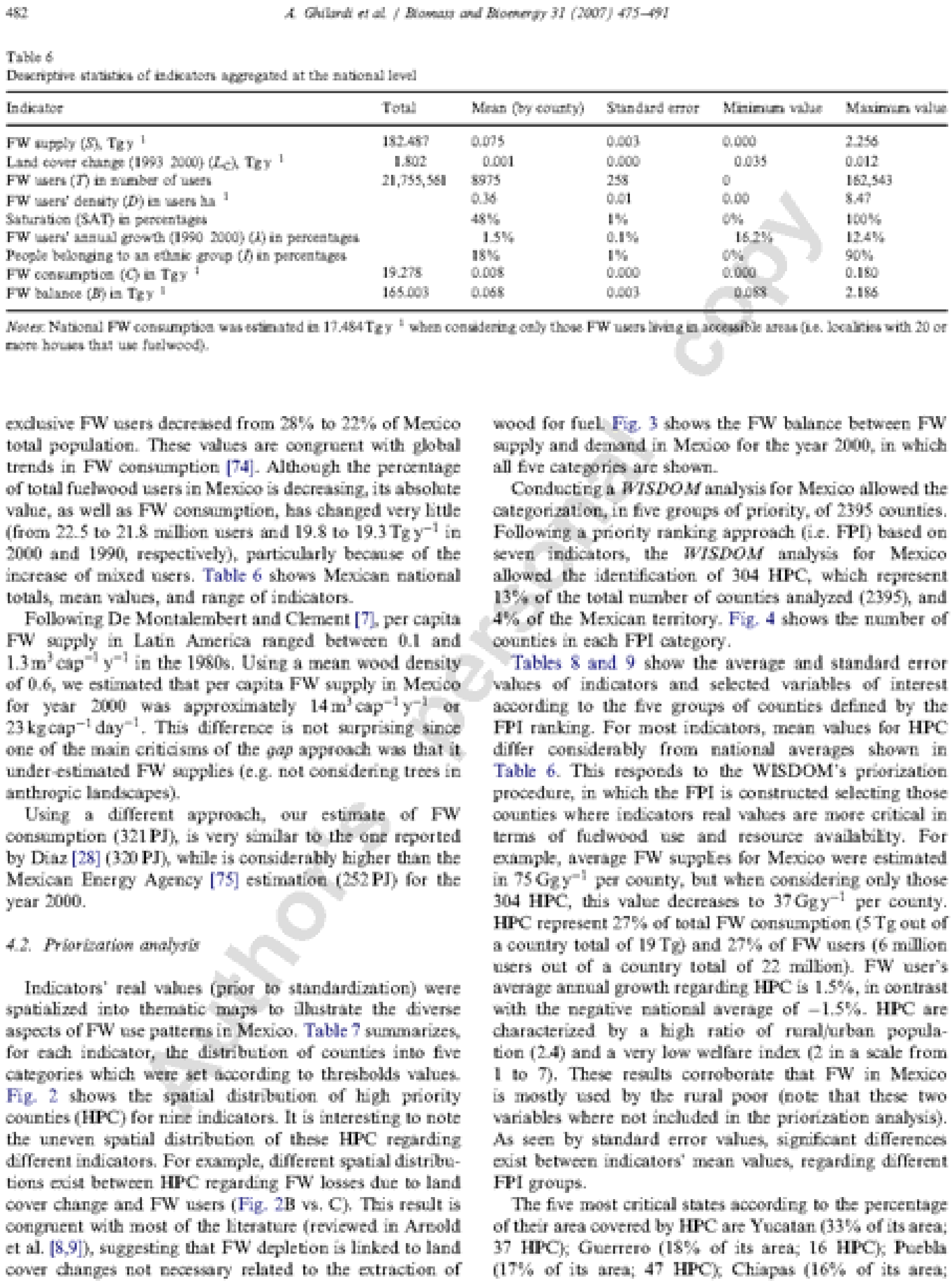


Table 6
Descriptive statistics of indicators aggregated at the national level

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	21,755,581	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) (*A*) 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).

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;

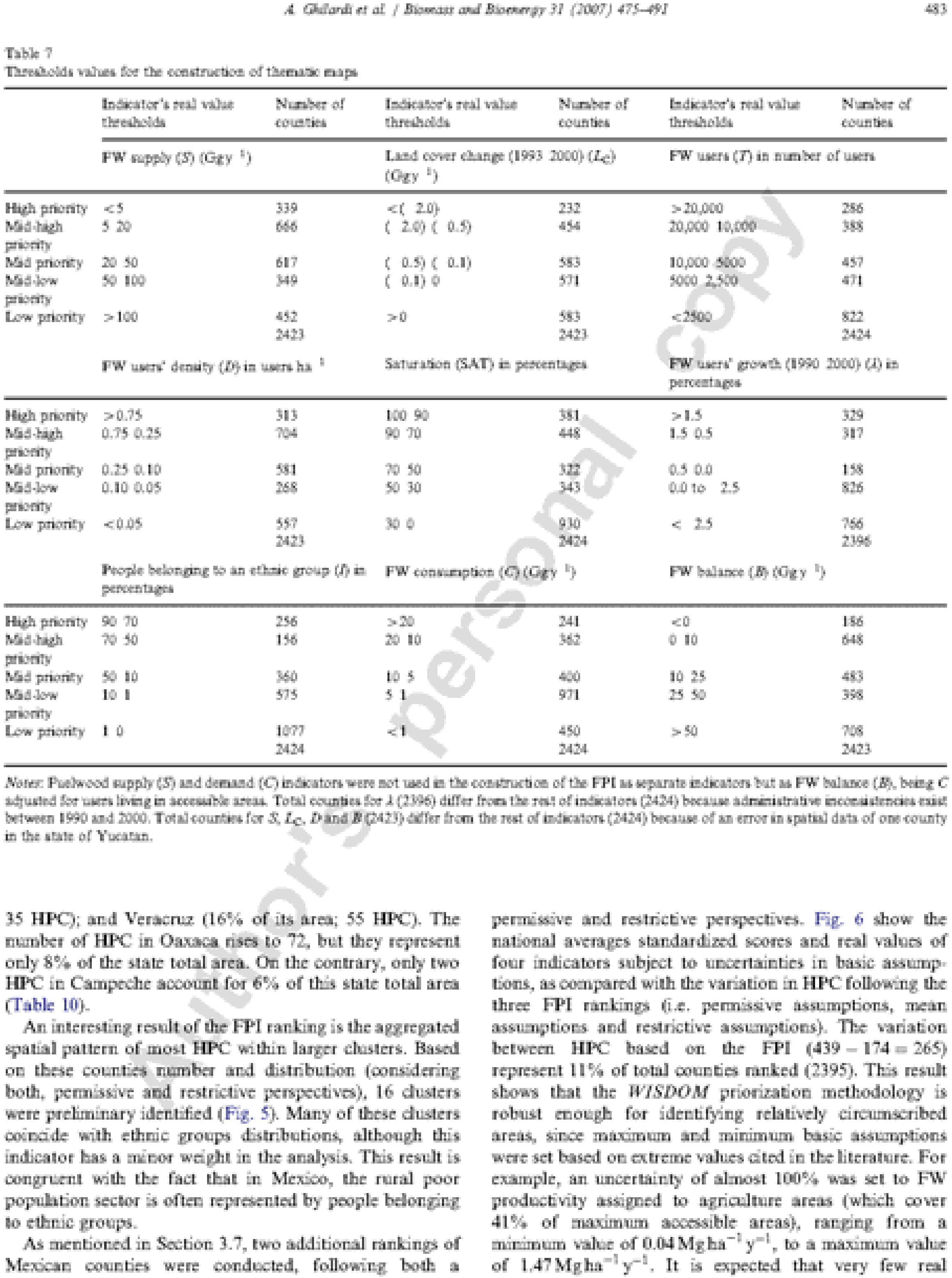


Table 7
Thresholds values for the construction of thematic maps

	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

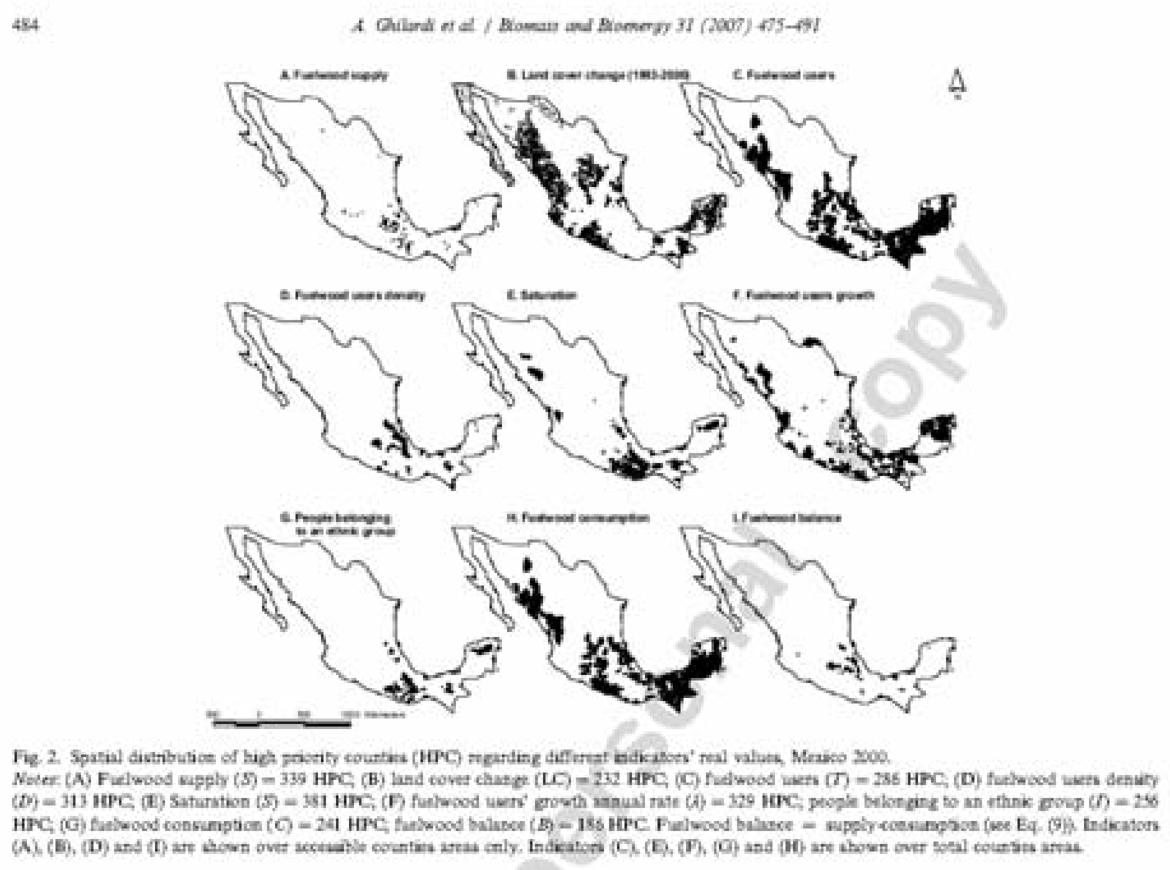


Fig. 2. Spatial distribution of high priority counties (HPC) regarding different indicators' real values, Mexico 2000.
Notes: (A) Fuelwood supply (S) = 339 HPC; (B) land cover change (LC) = 232 HPC; (C) fuelwood users (T) = 286 HPC; (D) fuelwood users density (D) = 313 HPC; (E) Saturation (S) = 381 HPC; (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

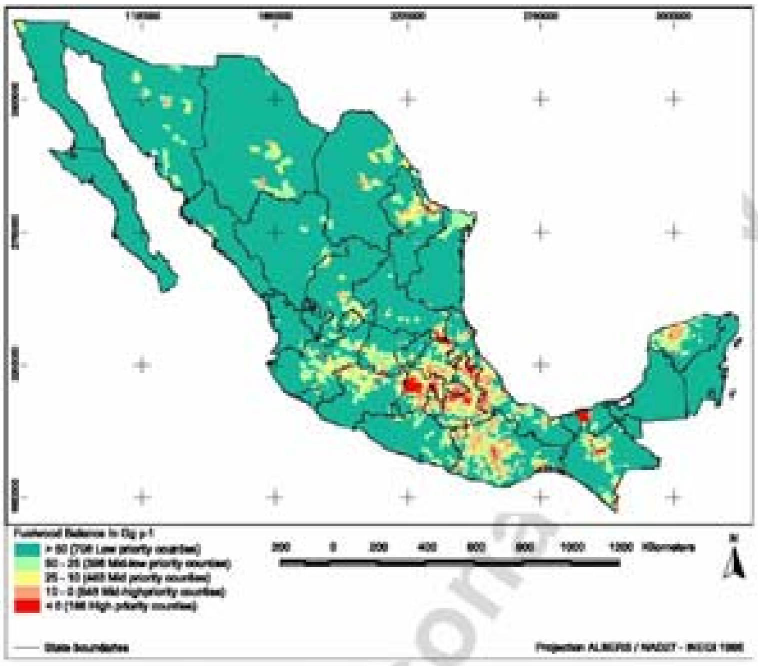


Fig. 3. Fuelwood balance between fuelwood supply and demand, Mexico 2000.

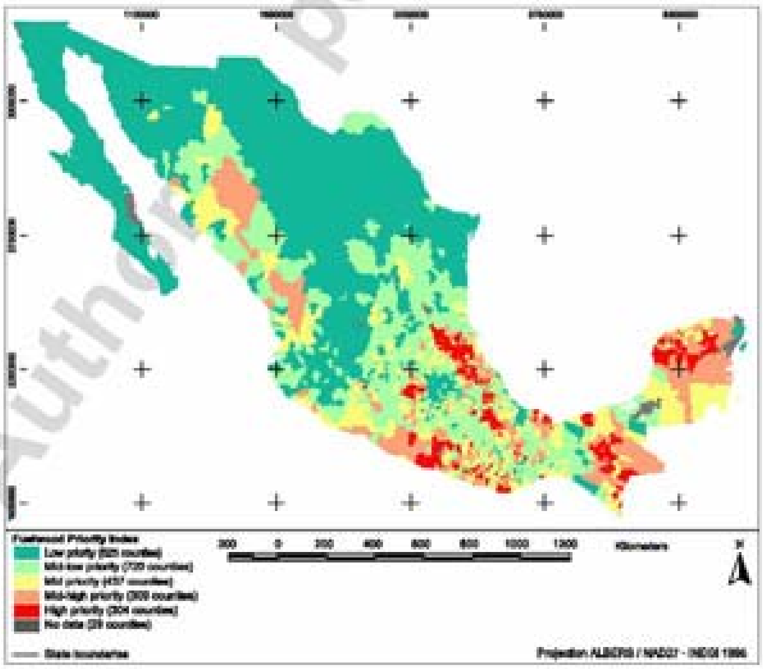


Fig. 4. Priority counties in terms of fuelwood use and availability of fuelwood resources, Mexico 2000.

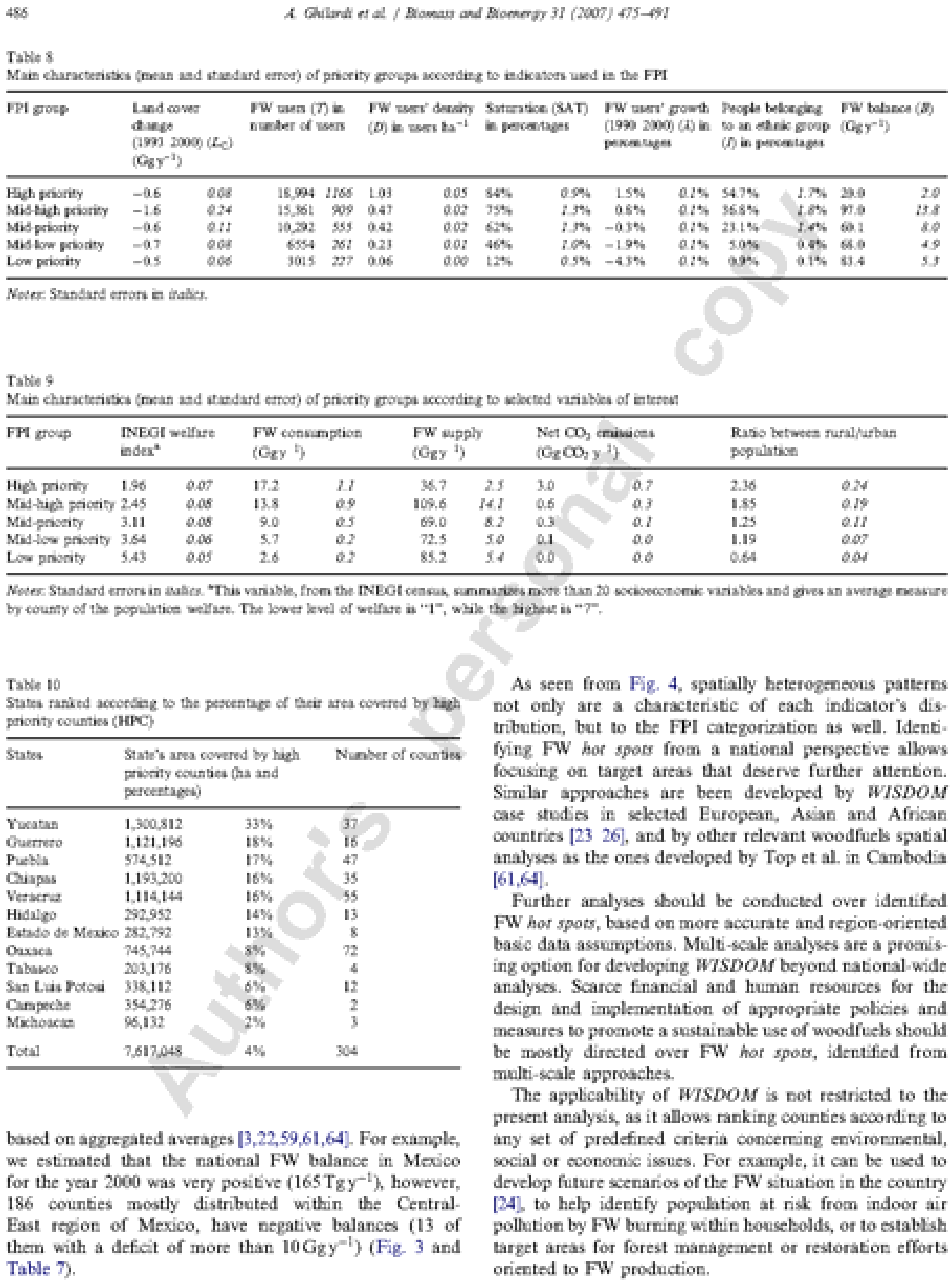


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Table 8
Main characteristics (mean and standard error) of priority groups according to indicators used in the FPI

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) (A) 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%*	0.6%	*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%*	69.1	*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%*	66.0	*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.

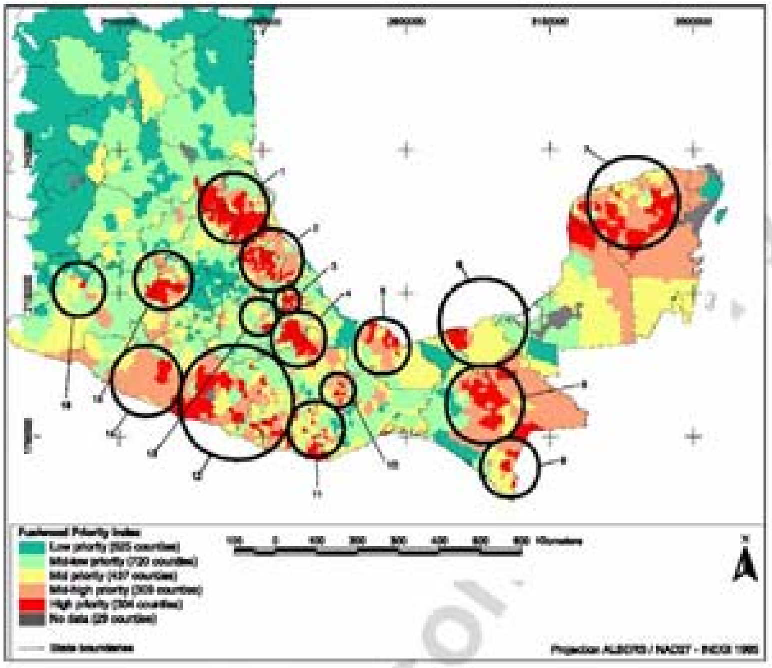

Fig. 5. Clusters of high priority counties (HPC), Mexico 2000.

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 coast; (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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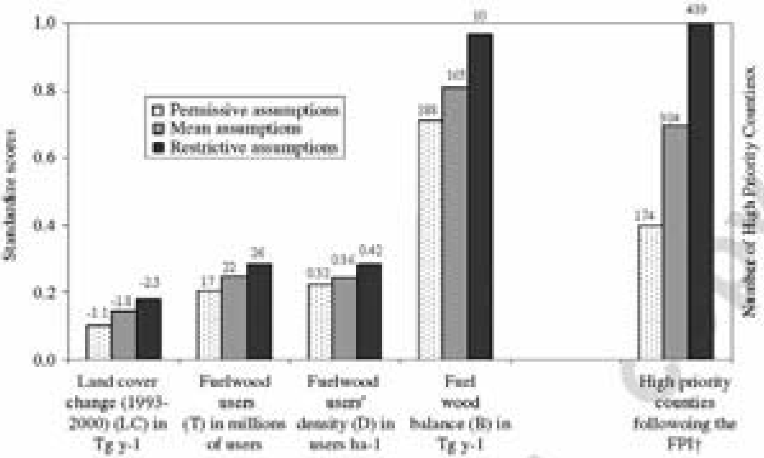


Fig. 6. National average standardized scores of indicators subject to permissive and restrictive assumptions.
Notes: Bars height corresponds to standardized scores. Values over bars corresponds to indicators' real values (prior to standardization, see also Table 7). (†) Values over bars correspond to 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.

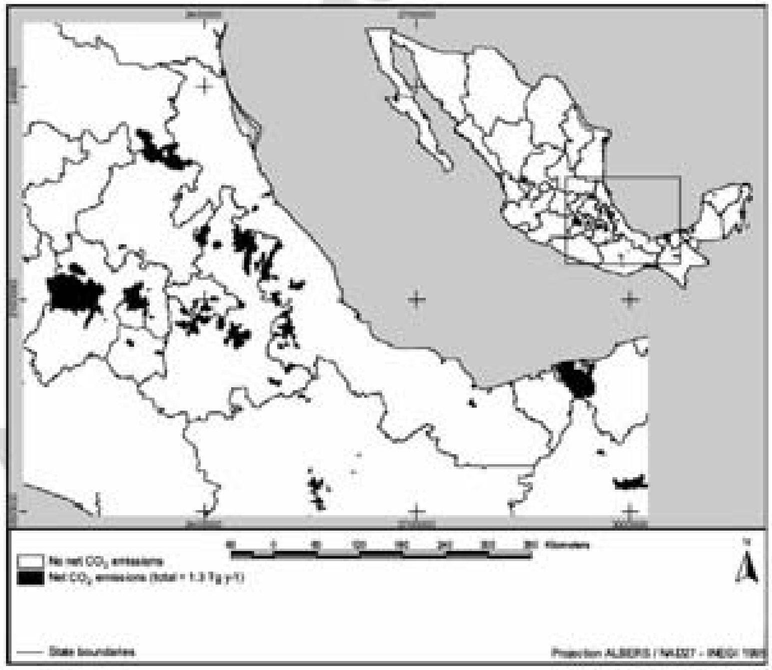
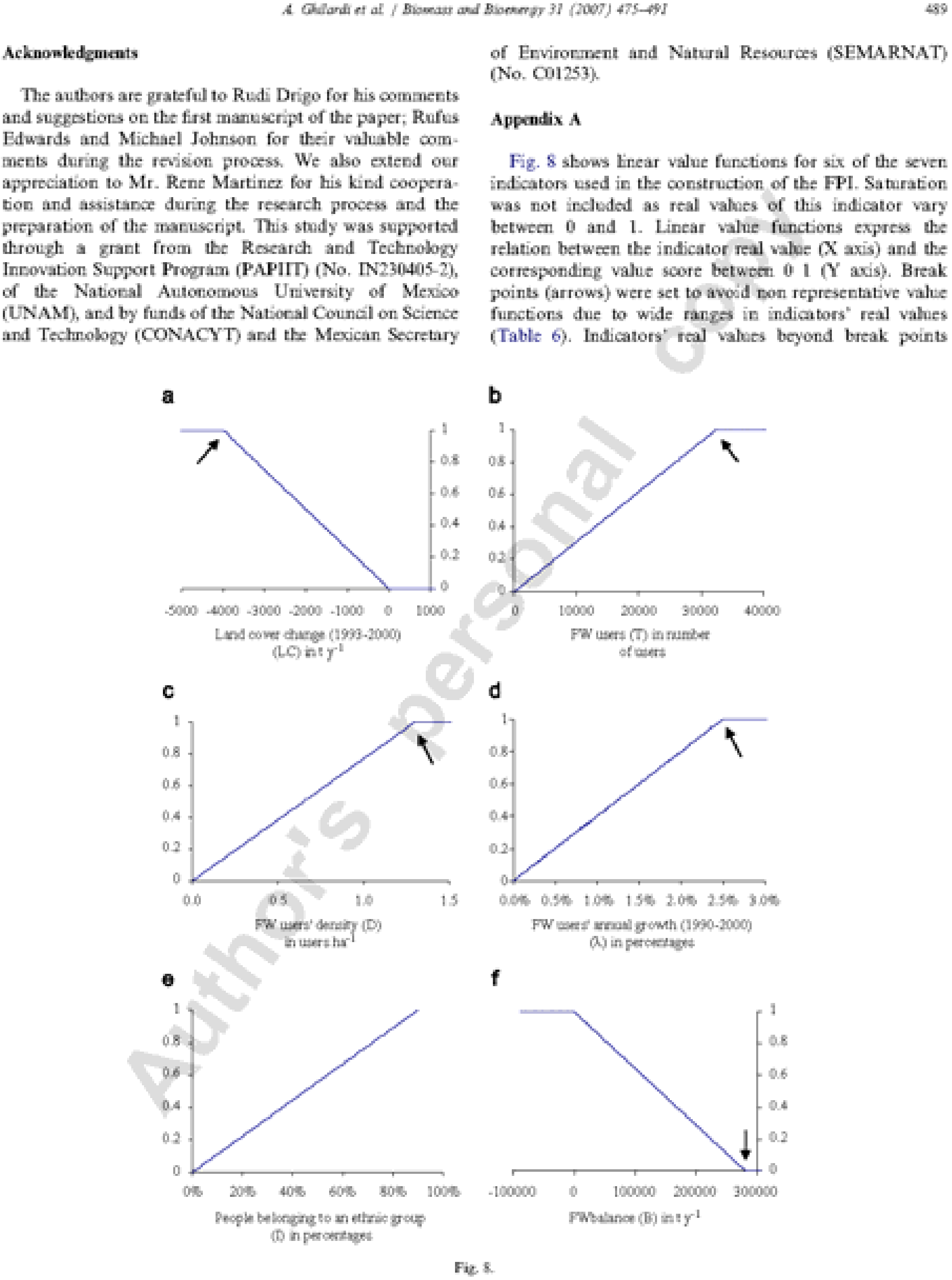


Fig. 7. Estimated net CO_2 emissions from the non-renewable use of fuelwood, Mexico 2000.



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Acknowledgments

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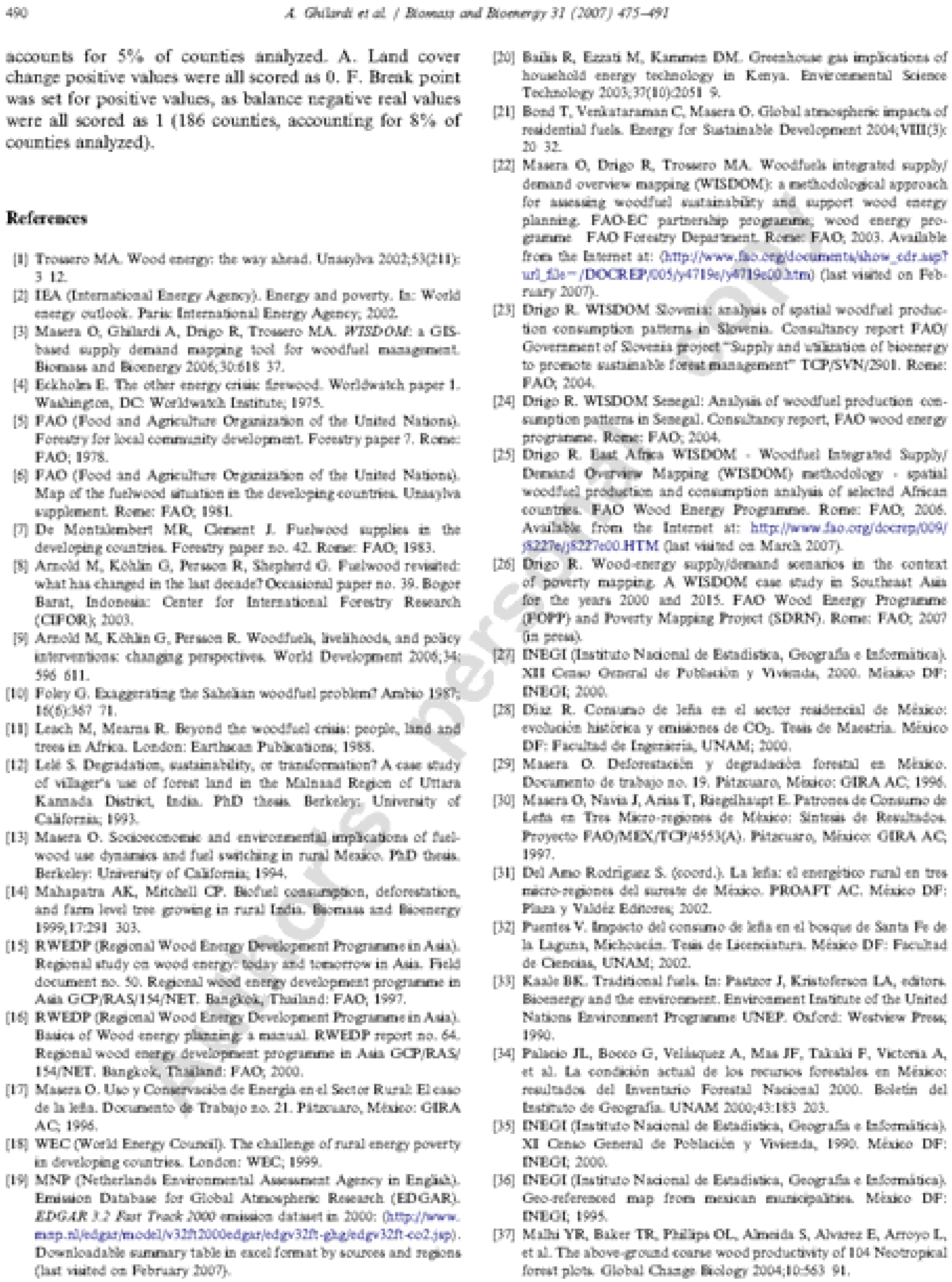
Appendix A

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.



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).

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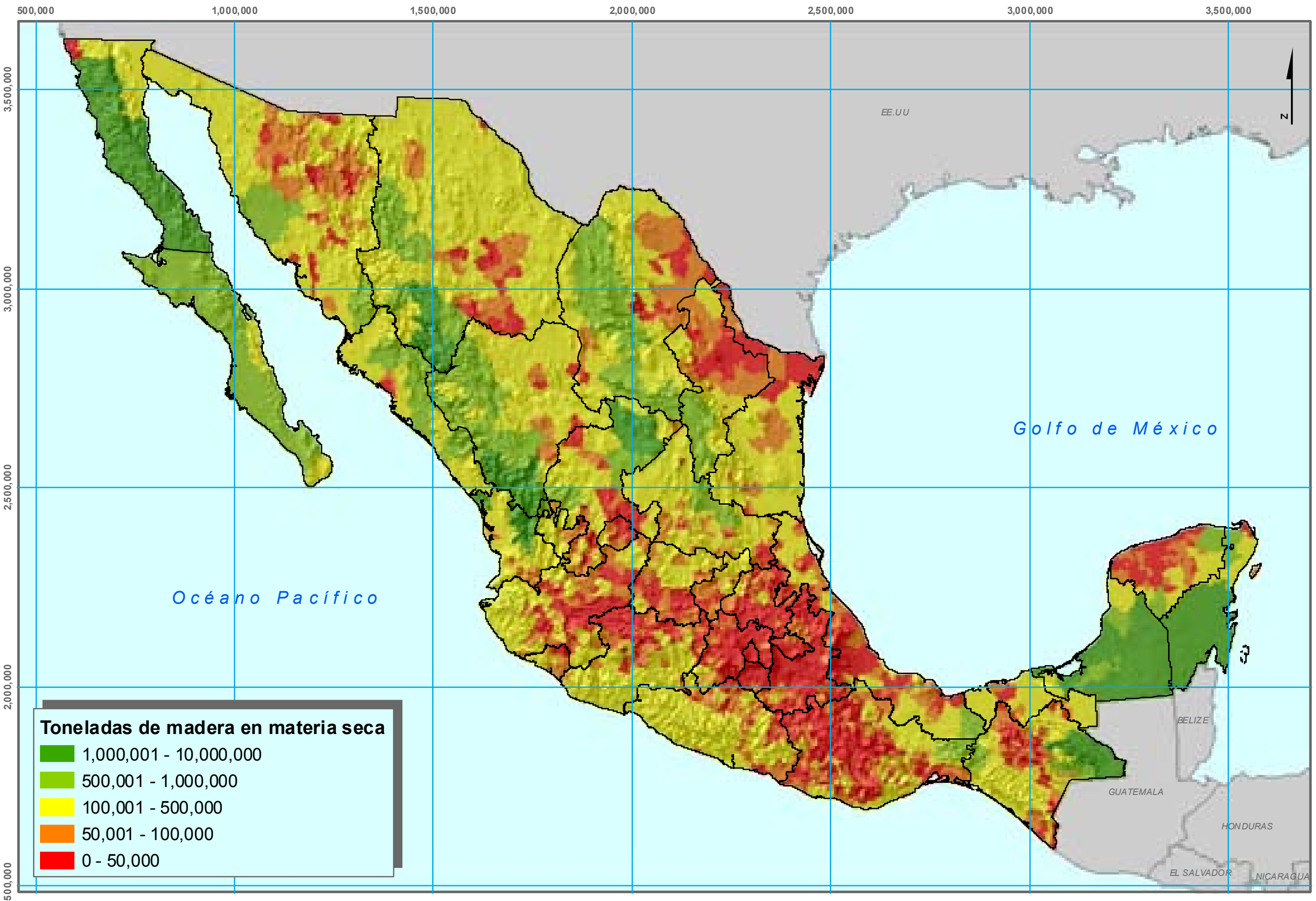
III.2 Mapas temáticos sobre oferta y demanda de leña por el sector residencial

Los mapas temáticos muestran como se distribuyen espacialmente diferentes variables asociadas a la oferta y demanda de leña para uso residencial en México. Como se mostró en la sección II.3, algunas de éstas variables fueron incorporadas en el análisis multi-criterio del modelo WISDOM a fin de definir las áreas críticas o *fuelwood hot spots* en términos de uso de leña y disponibilidad de recursos. Al final de la presente sección se incluyen los mapas correspondientes a éstas áreas críticas (figuras 4 y 5 de la sección anterior). Notar que el número de municipios críticos aumentó de 304 a 322; esto se debió a ajustes en los supuestos de base a partir de publicaciones posteriores a la sección III.1 de la presente Tesis (e.g.Berrueta *et al.*, 2007).

III.3 Caracteristicas de las áreas críticas en función de indicadores clave

Las tablas III.1 y III.2 muestran los valores promedio por municipio para un grupo de indicadores clave para las áreas críticas identificadas.

Figura III.1. Incremento anual de madera disponible para energía por municipio.



Incremento anual de madera disponible para energía por municipio en México - 2000

Areas accesibles de ***10km*** alrededor de localidades y ***3km*** al costado de caminos.
Productividad ***promedio*** de madera para energía por hectárea por año.

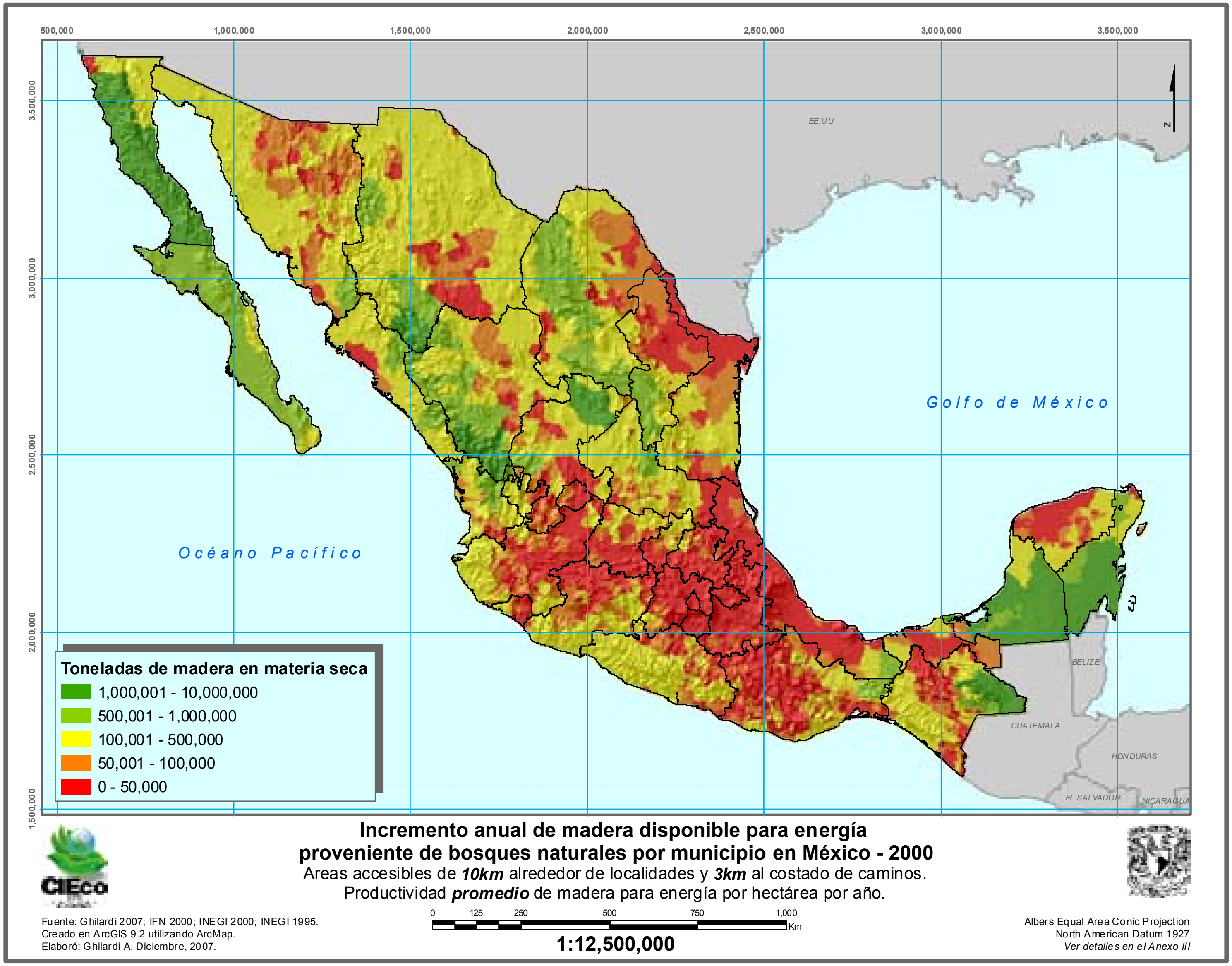
Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 125 250 500 750 1,000 Km

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.2. Incremento anual de madera disponible para energía proveniente de bosques naturales por municipio.



Incremento anual de madera disponible para energía proveniente de bosques naturales por municipio en México - 2000

Areas accesibles de ***10km*** alrededor de localidades y ***3km*** al costado de caminos.
Productividad ***promedio*** de madera para energía por hectárea por año.

1:12,500,000

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.3. Incremento anual de madera disponible para energía por hectárea por municipio.

Incremento anual de madera disponible para energía por hectárea por municipio en México - 2000

Areas accesibles de ***10km*** alrededor de localidades y ***3km*** al costado de caminos.
Productividad ***promedio*** de madera para energía por hectárea por año.

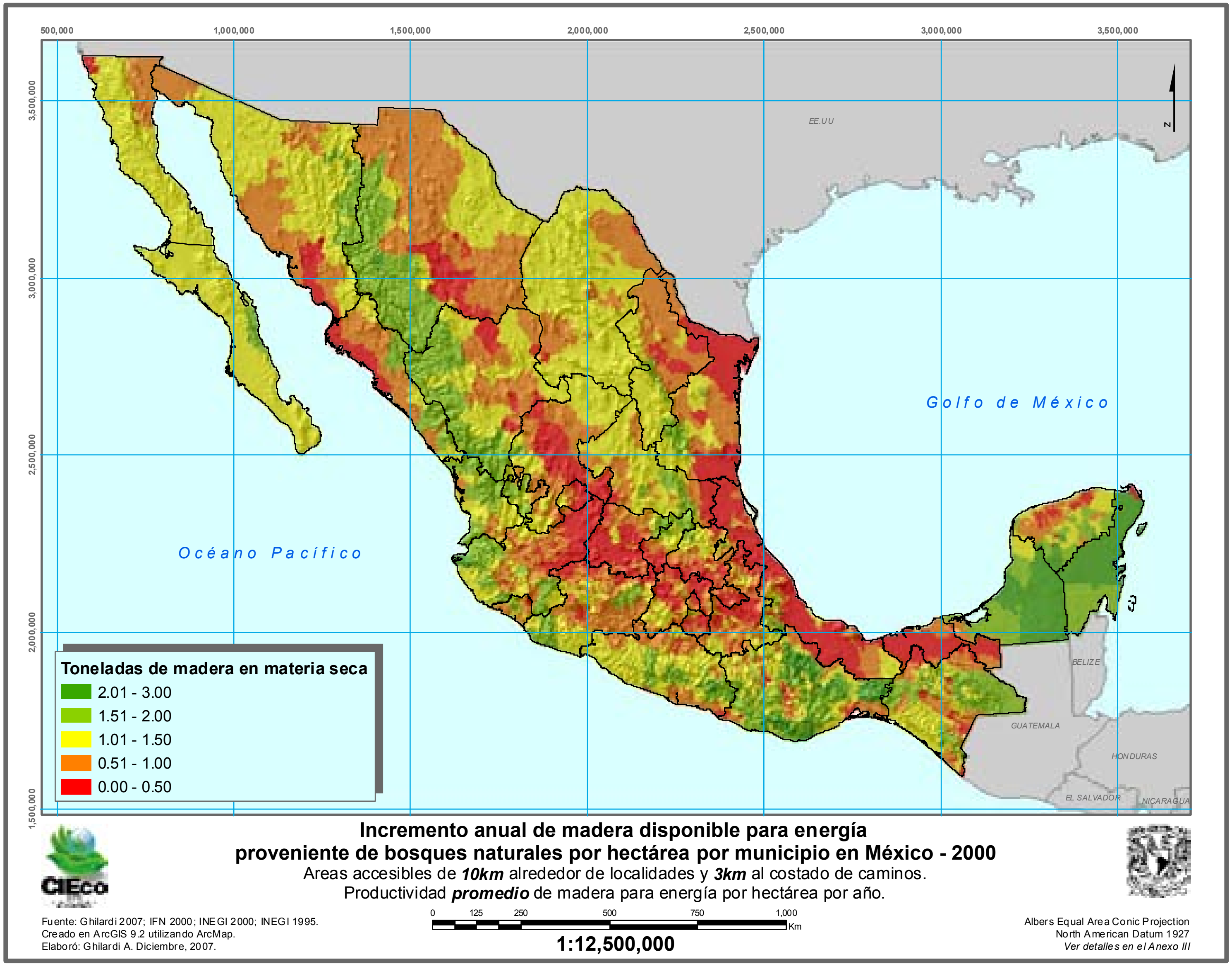
Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 125 250 500 750 1,000 Km

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.4. Incremento anual de madera disponible para energía proveniente de bosques naturales por hectárea por municipio.



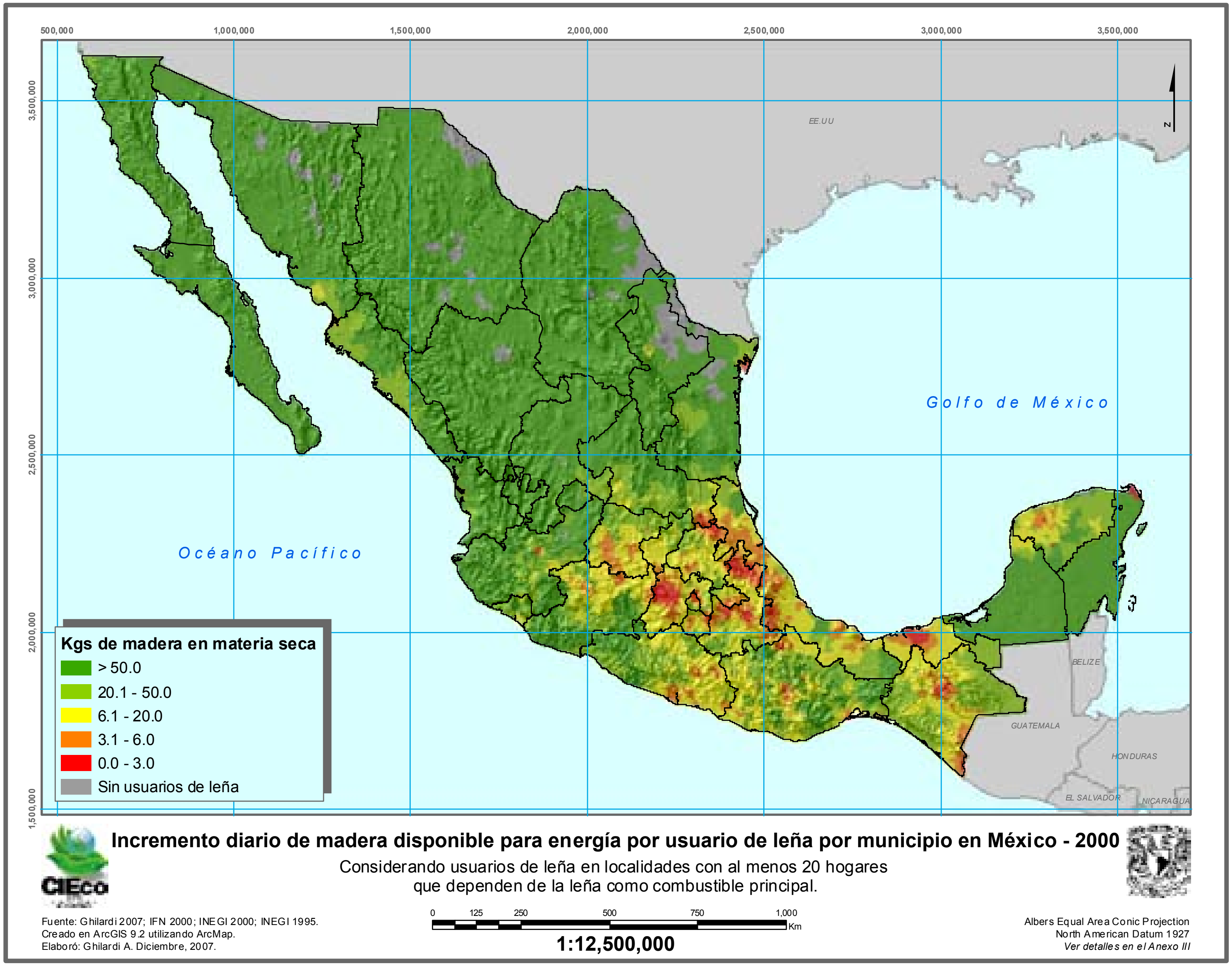
Incremento anual de madera disponible para energía
proveniente de bosques naturales por hectárea por municipio en México - 2000
Areas accesibles de ***10km*** alrededor de localidades y ***3km*** al costado de caminos.
Productividad ***promedio*** de madera para energía por hectárea por año.

1:12,500,000

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.5. Incremento diario de madera disponible para energía por usuario de leña por municipio.



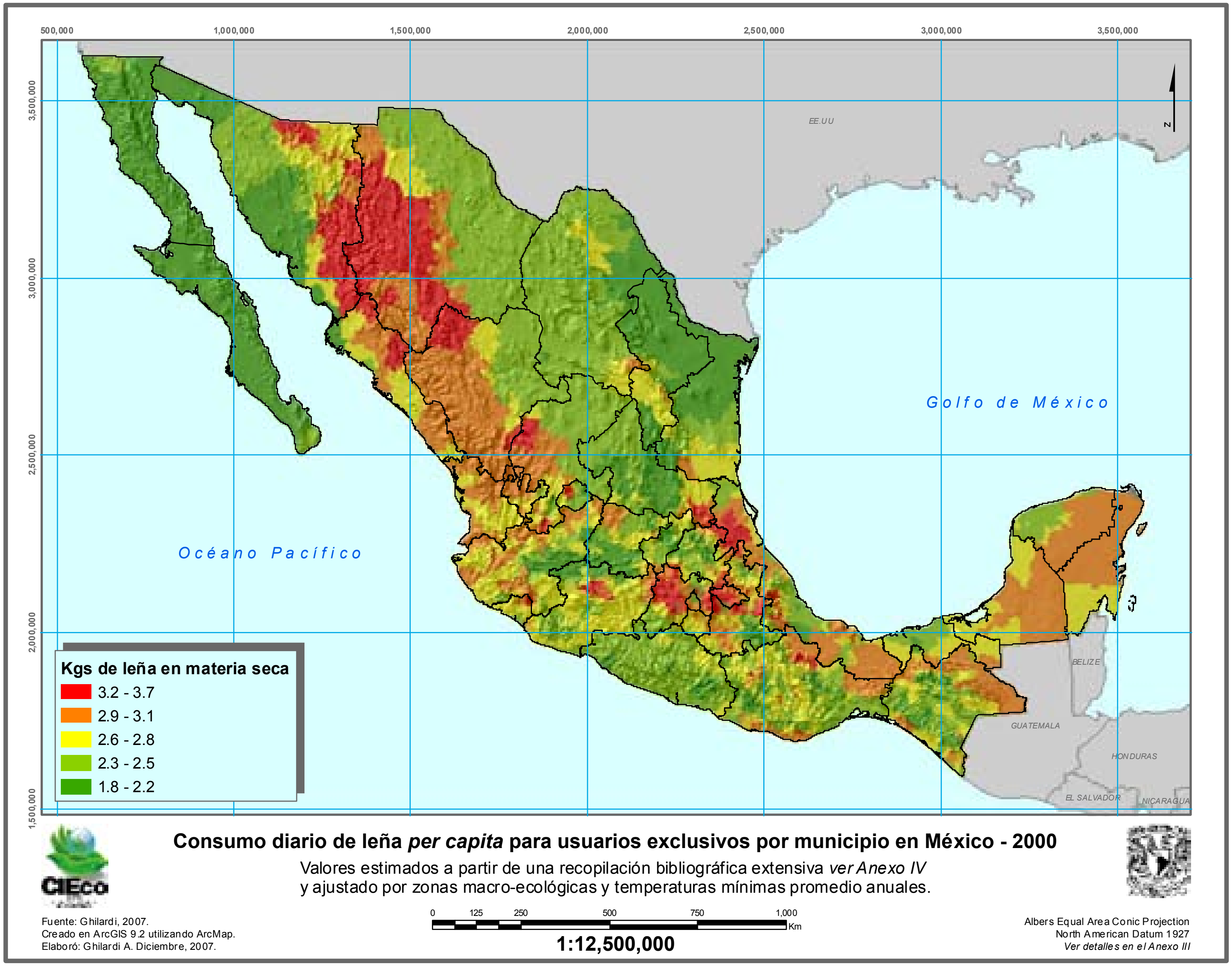
Incremento diario de madera disponible para energía por usuario de leña por municipio en México - 2000

Considerando usuarios de leña en localidades con al menos 20 hogares
que dependen de la leña como combustible principal.

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.6. Consumo diario de leña *per capita* por municipio para usuarios exclusivos.



Consumo diario de leña *per capita* para usuarios exclusivos por municipio en México - 2000

Valores estimados a partir de una recopilación bibliográfica extensiva *ver Anexo IV*
y ajustado por zonas macro-ecológicas y temperaturas mínimas promedio anuales.

Fuente: Ghilardi, 2007.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.7. Consumo diario de leña *per capita* por municipio para usuarios mixtos.

Consumo diario de leña *per capita* para usuarios mixtos por municipio en México - 2000

Valores estimados a partir de una recopilación bibliográfica extensiva *ver Anexo IV*
y ajustado por zonas macro-ecológicas y temperaturas mínimas promedio anuales.

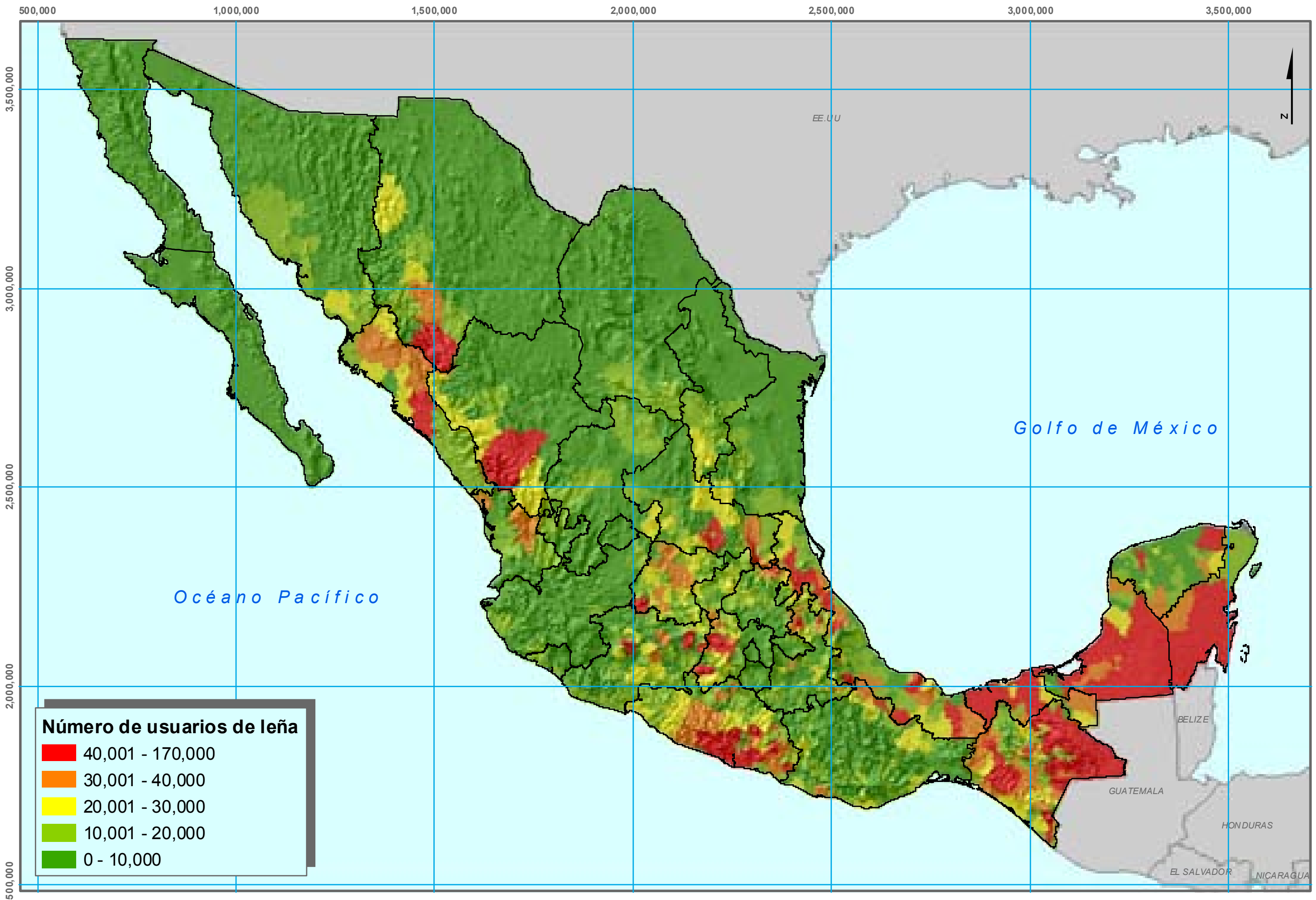
Fuente: Ghilardi, 2007.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 125 250 500 750 1,000 Km

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.8. Número de usuarios de leña (exclusivos y mixtos) por municipio.



Número de usuarios de leña (exclusivos y mixtos) por municipio en México - 2000

Valores estimados a partir del XII Censo de Población y Vivienda 2000 del INEGI junto a una recopilación bibliográfica extensiva que permitió ajustar por el número de usuarios mixtos no censados *ver Anexo IV.*

Fuente: Ghilardi, 2007; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 125 250 500 750 1,000 Km

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.9. Densidad de usuarios de leña (exclusivos y mixtos) por municipio.

Número de usuarios de leña (exclusivos y mixtos) por hectárea por municipio en México - 2000

Valores estimados a partir del XII Censo de Población y Vivienda 2000 del INEGI junto a una recopilación bibliográfica extensiva que permitió ajustar por el número de usuarios mixtos no censados *ver Anexo IV*.

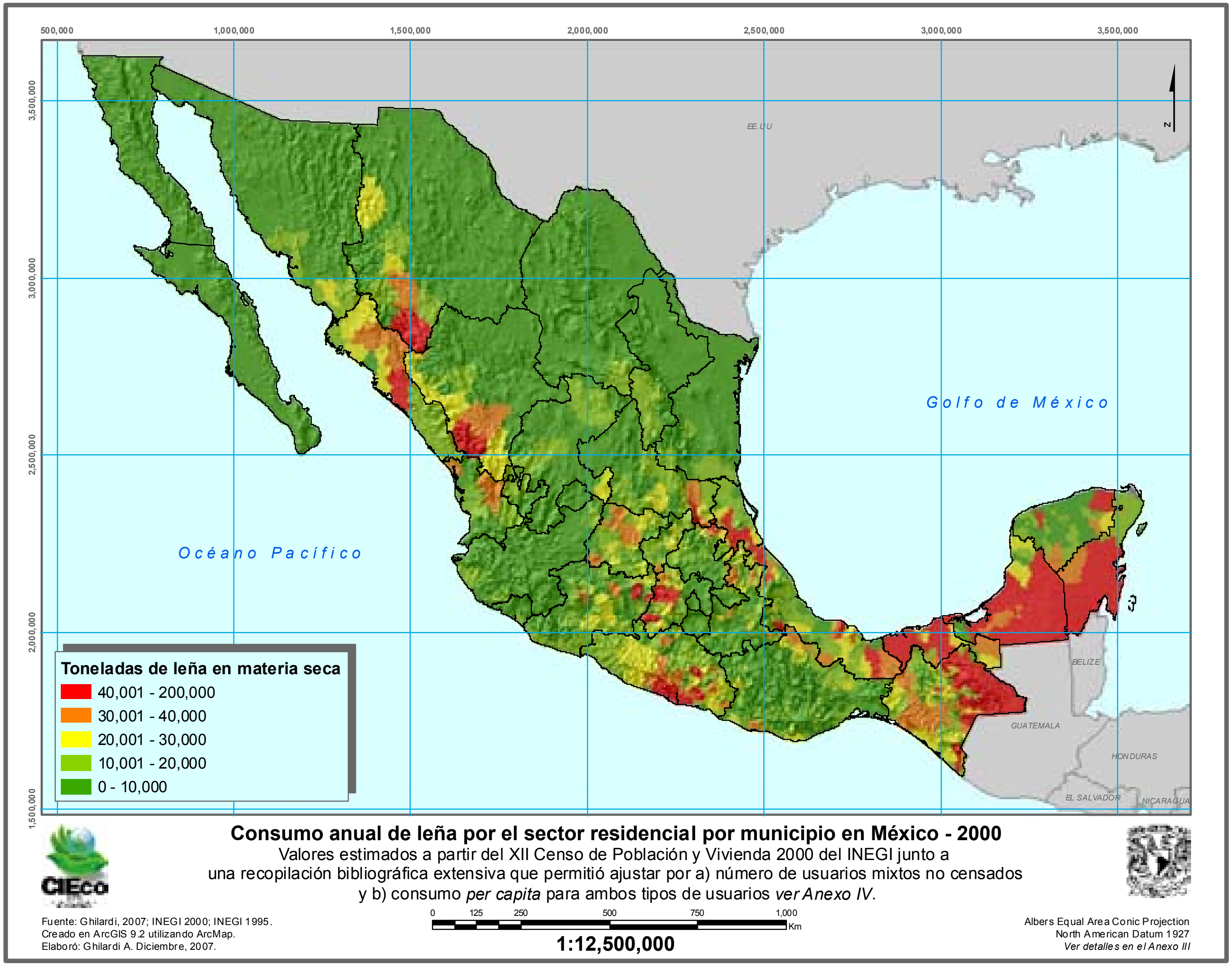
Fuente: Ghilardi, 2007; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 125 250 500 750 1,000 Km

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.10. Consumo anual de leña por el sector residencial por municipio.



Consumo anual de leña por el sector residencial por municipio en México - 2000

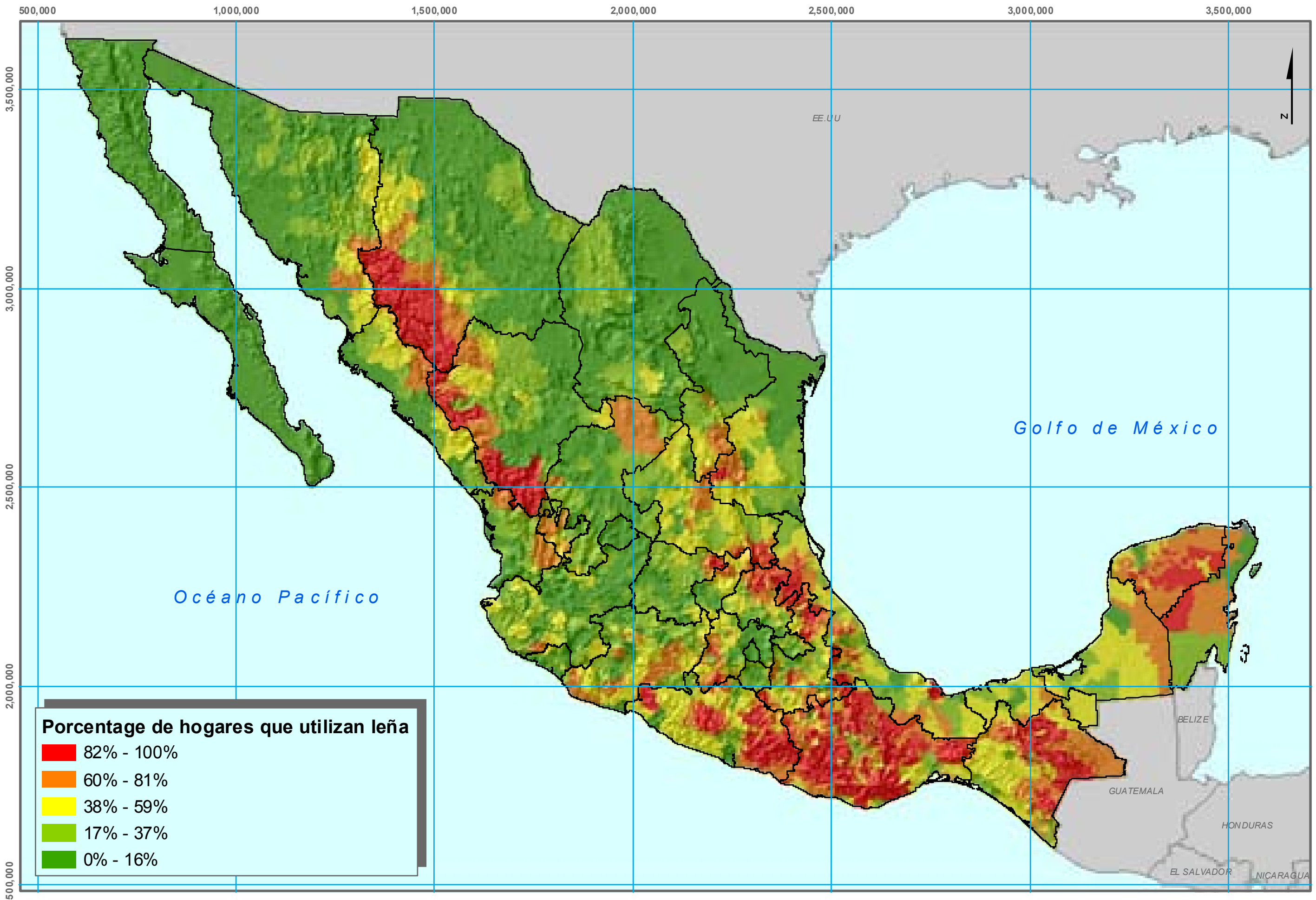
Valores estimados a partir del XII Censo de Población y Vivienda 2000 del INEGI junto a una recopilación bibliográfica extensiva que permitió ajustar por a) número de usuarios mixtos no censados y b) consumo *per capita* para ambos tipos de usuarios *ver Anexo IV*.

Fuente: Ghilardi, 2007; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.11. Porcentage de hogares que utilizan leña (saturación).



Porcentage de hogares que utilizan leña por municipio en México - 2000

Valores estimados a partir del XII Censo de Población y Vivienda 2000 del INEGI.

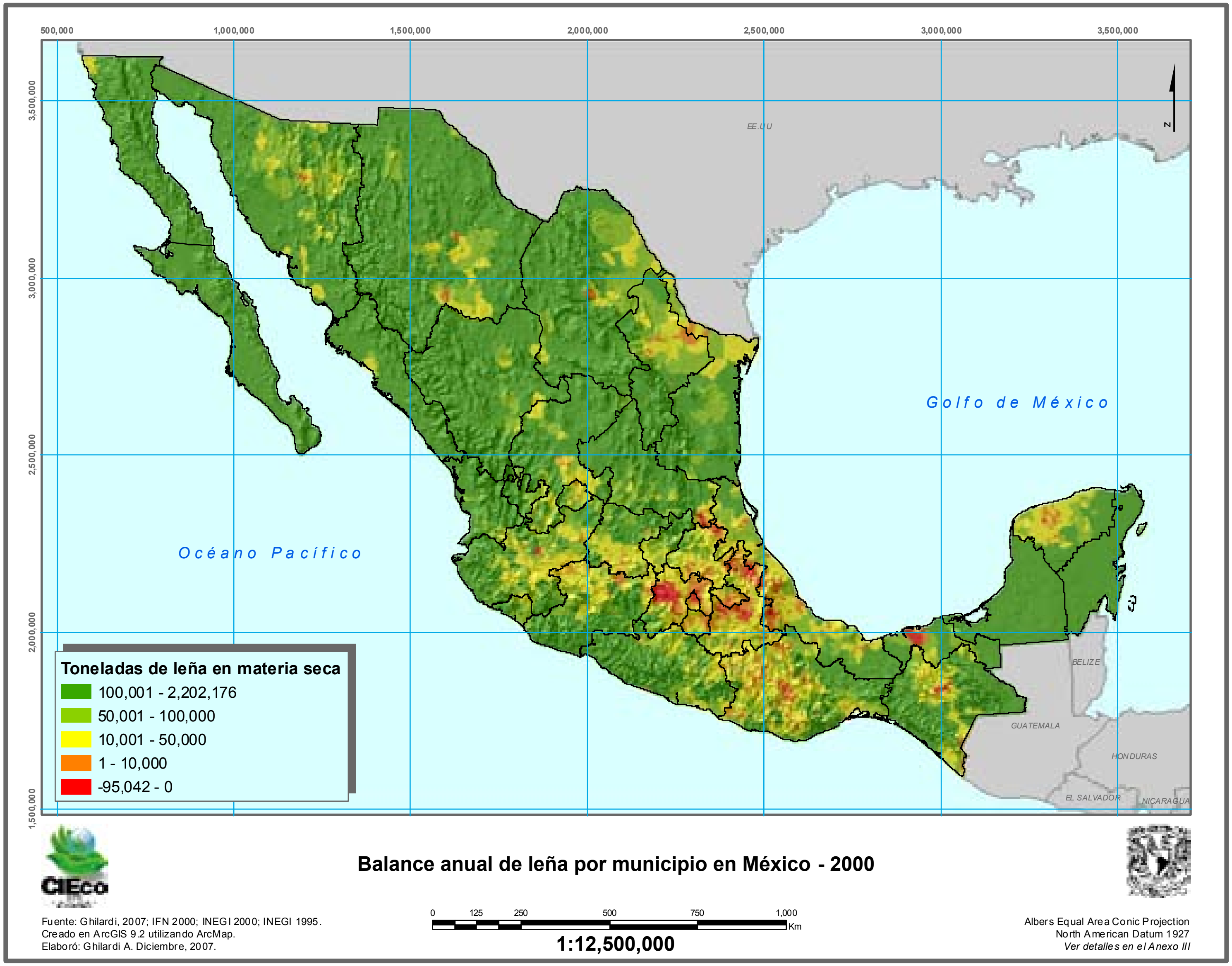
Fuente: Ghilardi, 2007; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 125 250 500 750 1,000 Km

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.12. Balance entre la disponibilidad de madera para energía y el consuno de leña por el sector residencial.



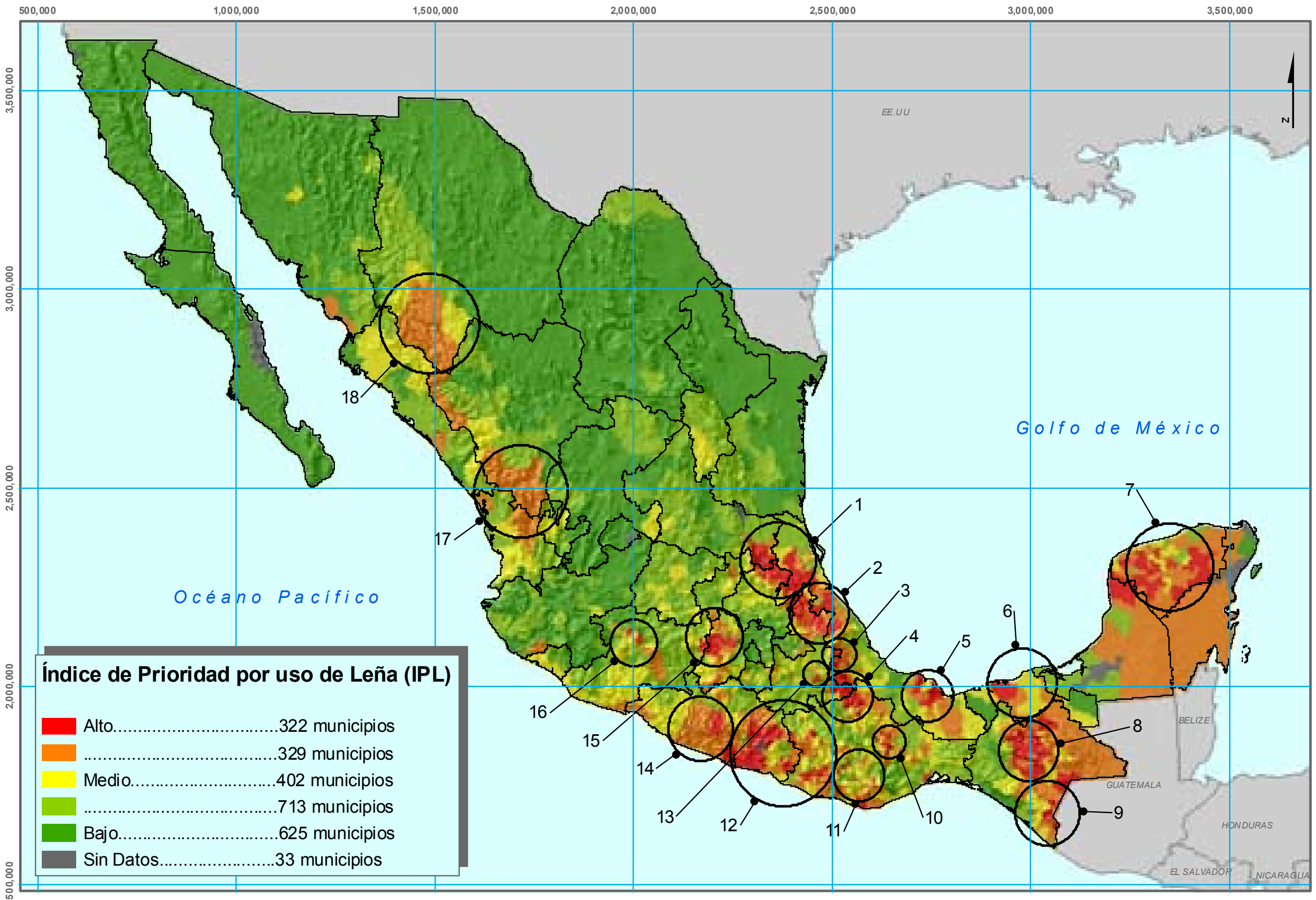
Balance anual de leña por municipio en México - 2000

Fuente: Ghilardi, 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.13. Áreas críticas en términos de uso de leña por el sector residencial y recursos disponibles.



Áreas prioritarias por uso residencial de leña en México - 2000

Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 125 250 500 750 1,000 Km

1:12,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.14. Áreas críticas en términos de uso de leña por el sector residencial y recursos disponibles (detalle).

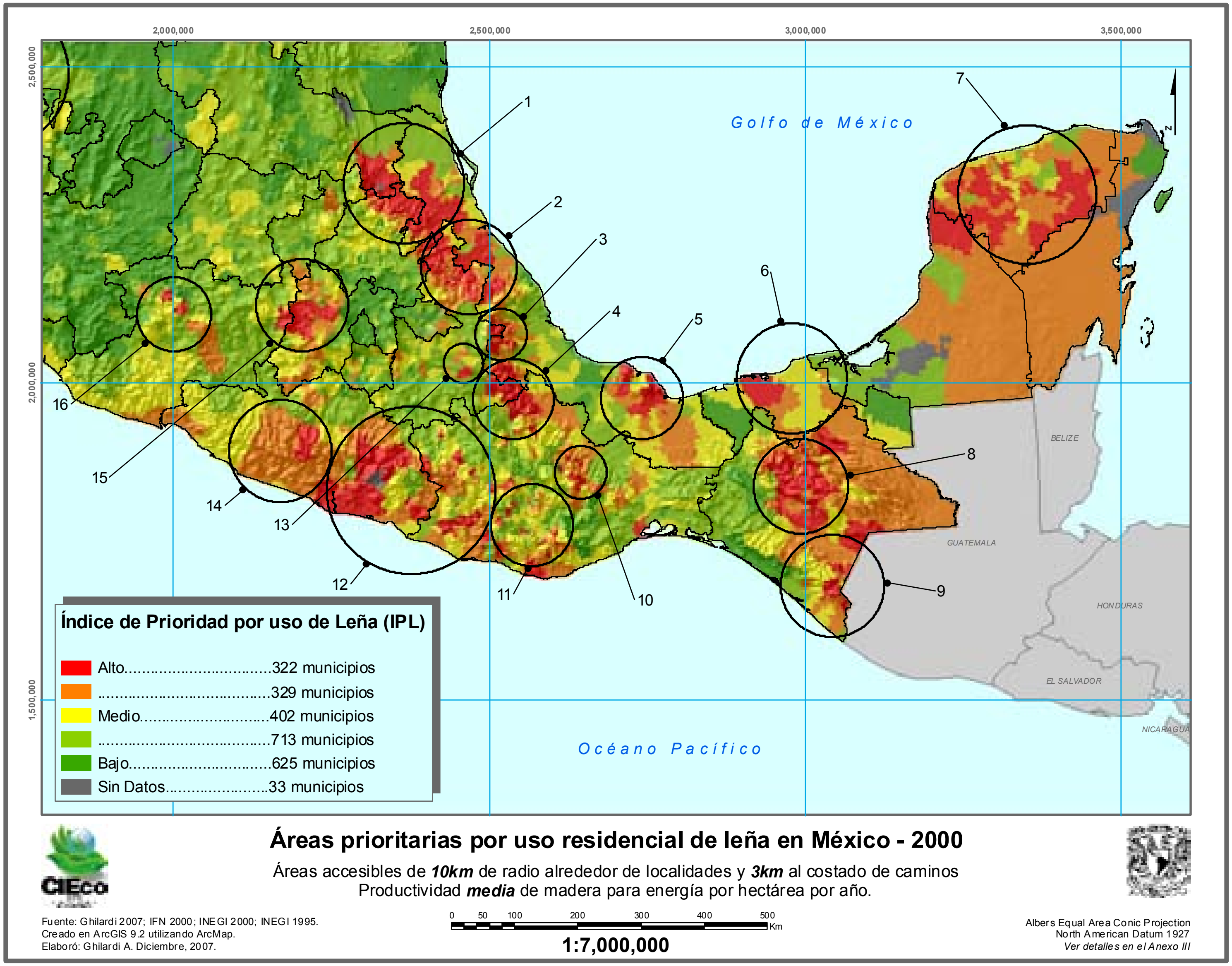
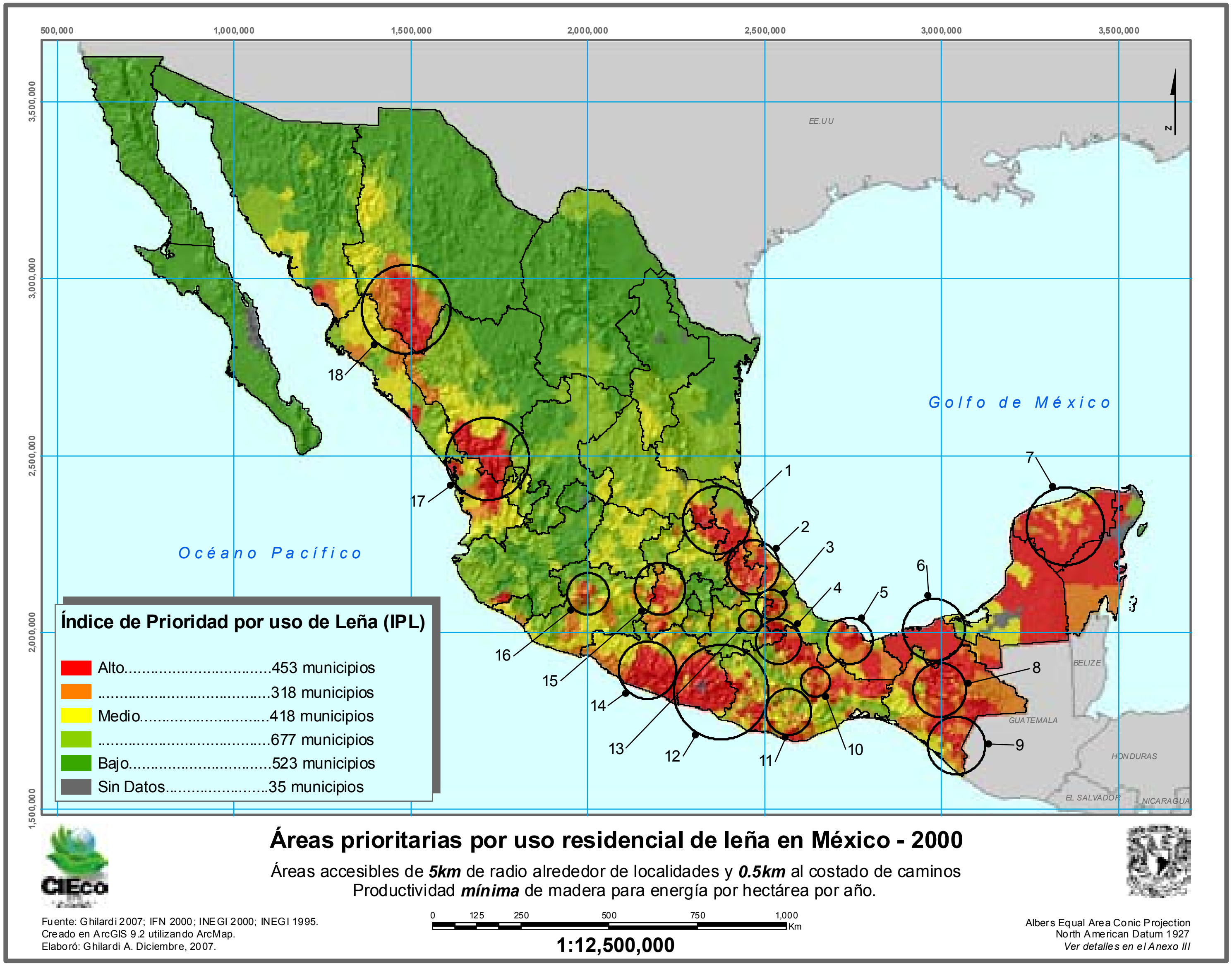


Figura III.15. Áreas críticas en términos de uso de leña por el sector residencial y recursos disponibles - supuestos restrictivos.



Áreas prioritarias por uso residencial de leña en México - 2000

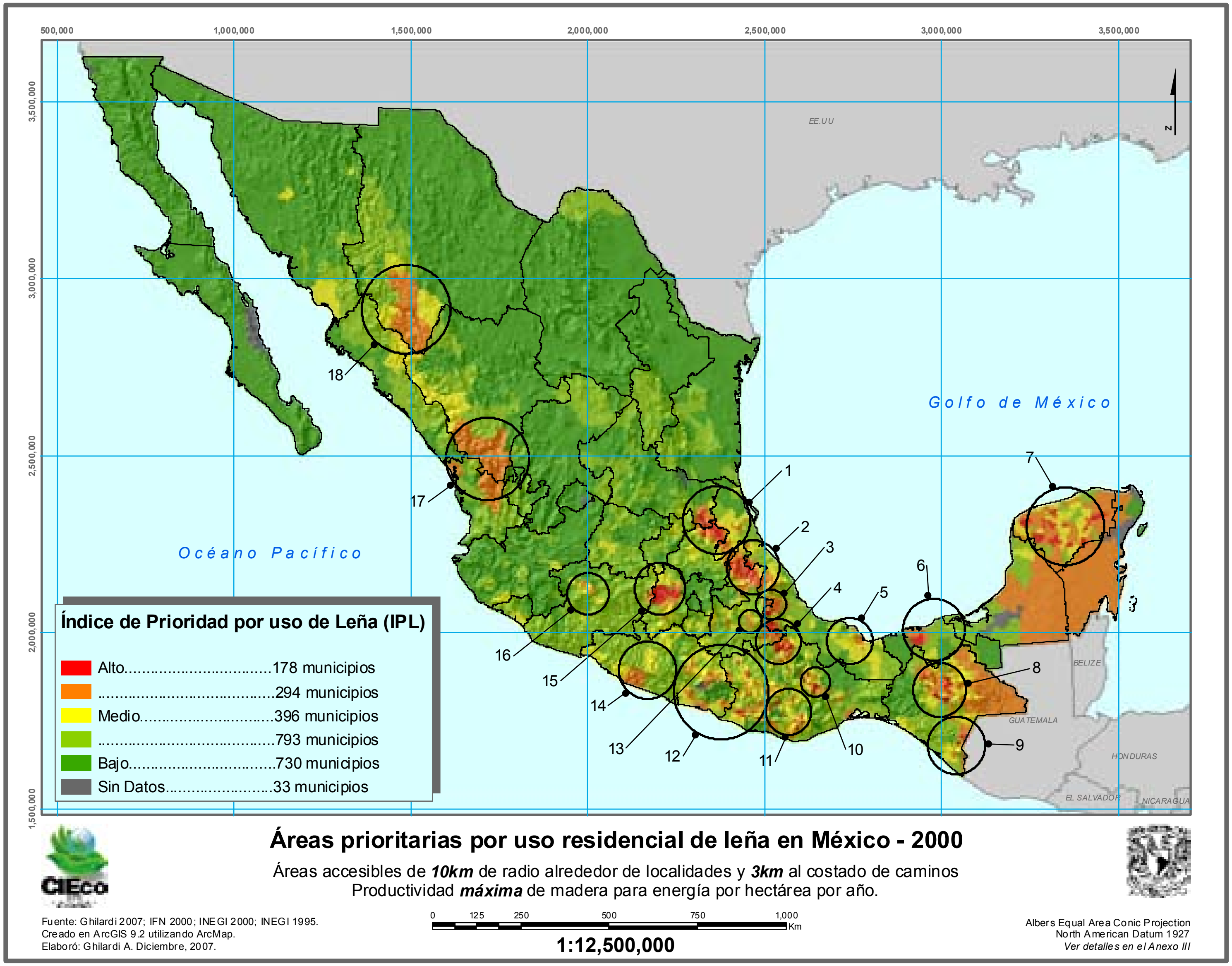
Áreas accesibles de ***5km*** de radio alrededor de localidades y ***0.5km*** al costado de caminos
Productividad ***mínima*** de madera para energía por hectárea por año.

1:12,500,000

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.16. Áreas críticas en términos de uso de leña por el sector residencial y recursos disponibles - supuestos permisivos.



Áreas prioritarias por uso residencial de leña en México - 2000

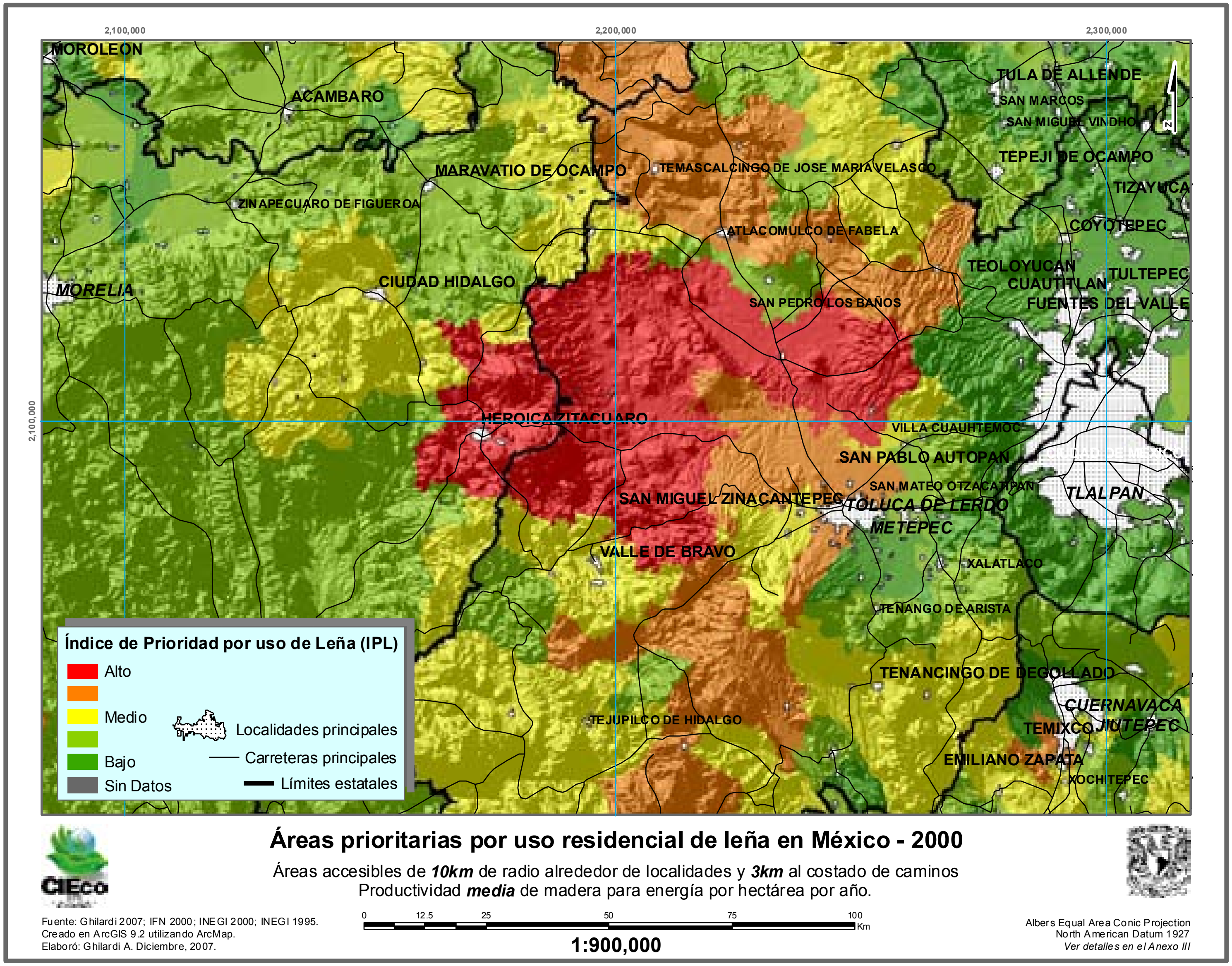
Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***máxima*** de madera para energía por hectárea por año.

1:12,500,000

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.17. Área crítica Nº15: regiones Otomí y Mazahua en los Estados de México y Michoacán.



Áreas prioritarias por uso residencial de leña en México - 2000

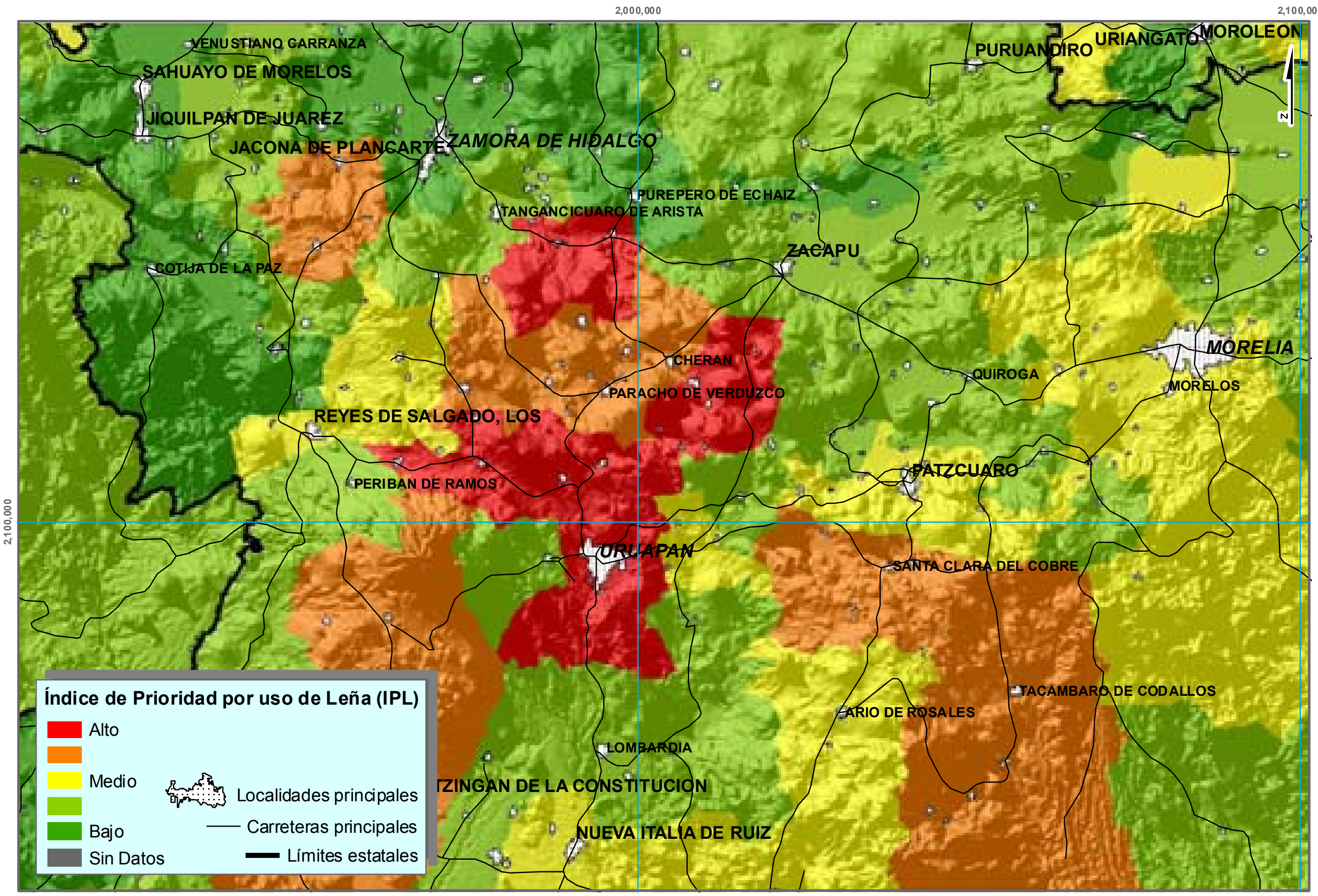
Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

1:900,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.18. Área crítica Nº16: región Purhépecha en el Estado de Michoacán.



Áreas prioritarias por uso residencial de leña en México - 2000

Áreas accesibles de ***5km*** de radio alrededor de localidades y ***0.5km*** al costado de caminos
Productividad ***mínima*** de madera para energía por hectárea por año.

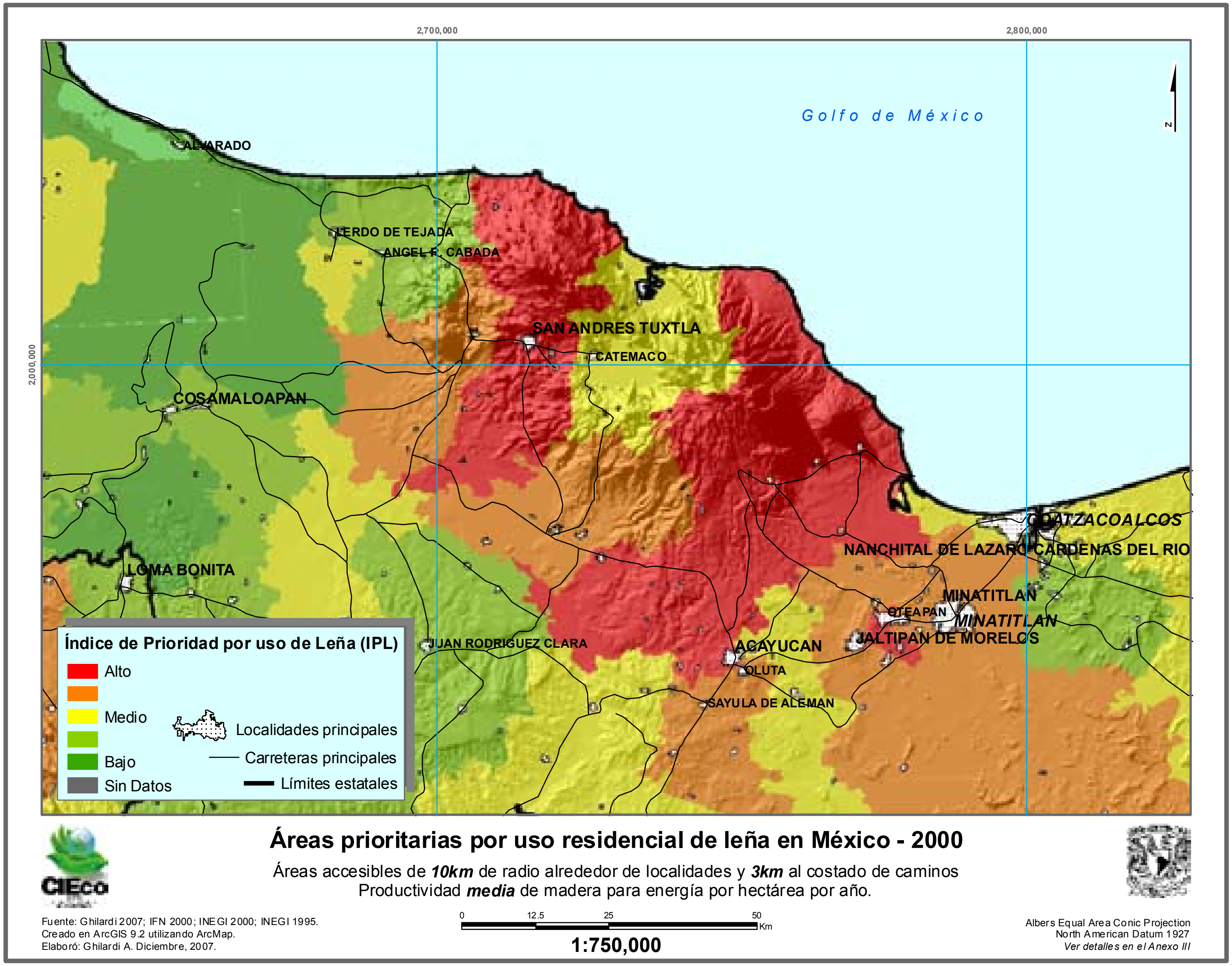
Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 12.5 25 50 Km

1:750,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.19. Área crítica Nº5: Los Tuxlas en el Estado de Veracruz.



Áreas prioritarias por uso residencial de leña en México - 2000

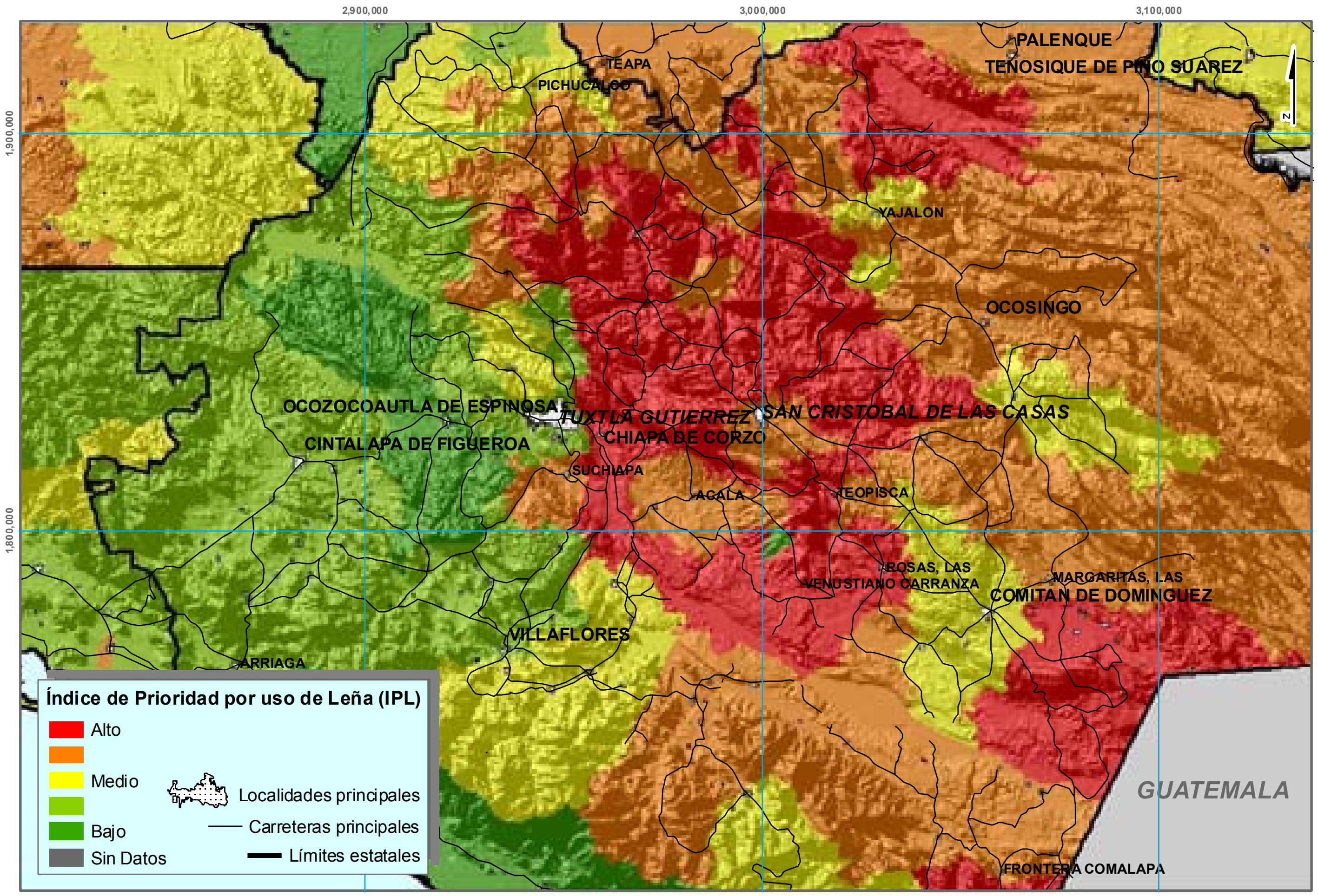
Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

1:750,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.20. Área crítica Nº8: Altos de Chiapas.



Áreas prioritarias por uso residencial de leña en México - 2000

Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

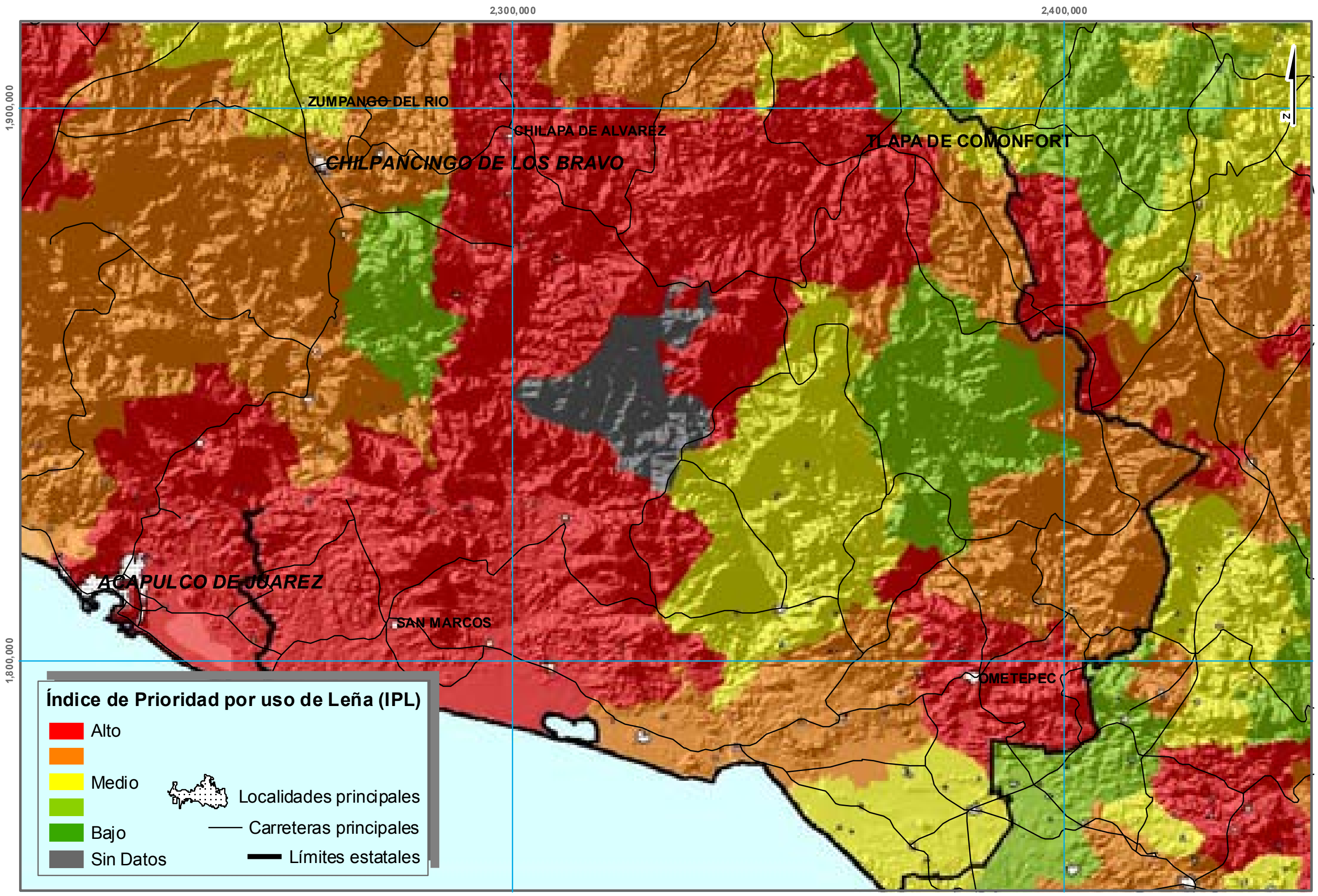
Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 12.5 25 50 75 100 Km

1:1,250,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.21. Área crítica Nº12: montaña de Guerrero.



Áreas prioritarias por uso residencial de leña en México - 2000

Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

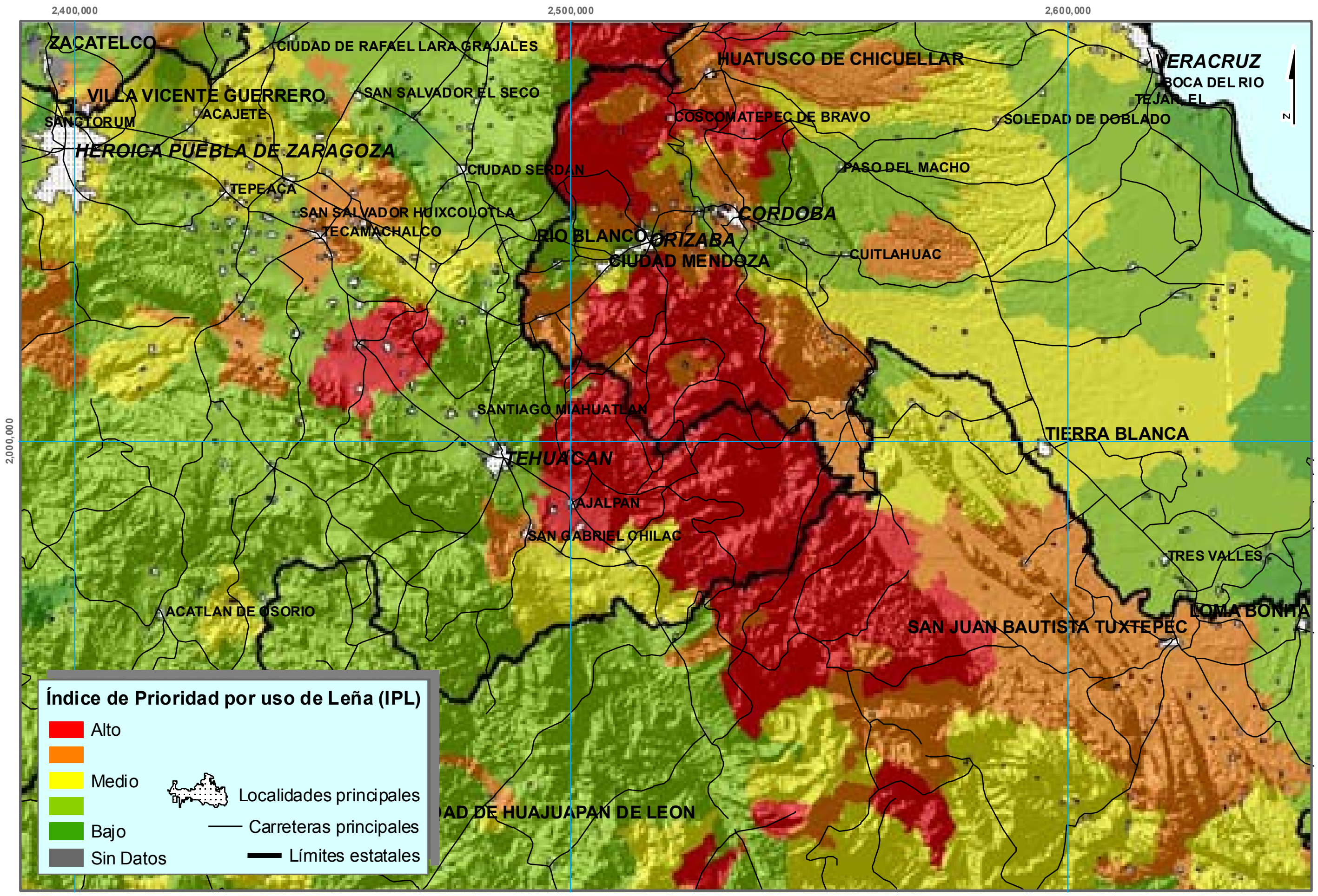
Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 12.5 25 50 75 100 Km

1:900,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.22. Área crítica Nº4: frontera entre los estados de Veracruz, Puebla y Oaxaca.



Áreas prioritarias por uso residencial de leña en México - 2000

Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

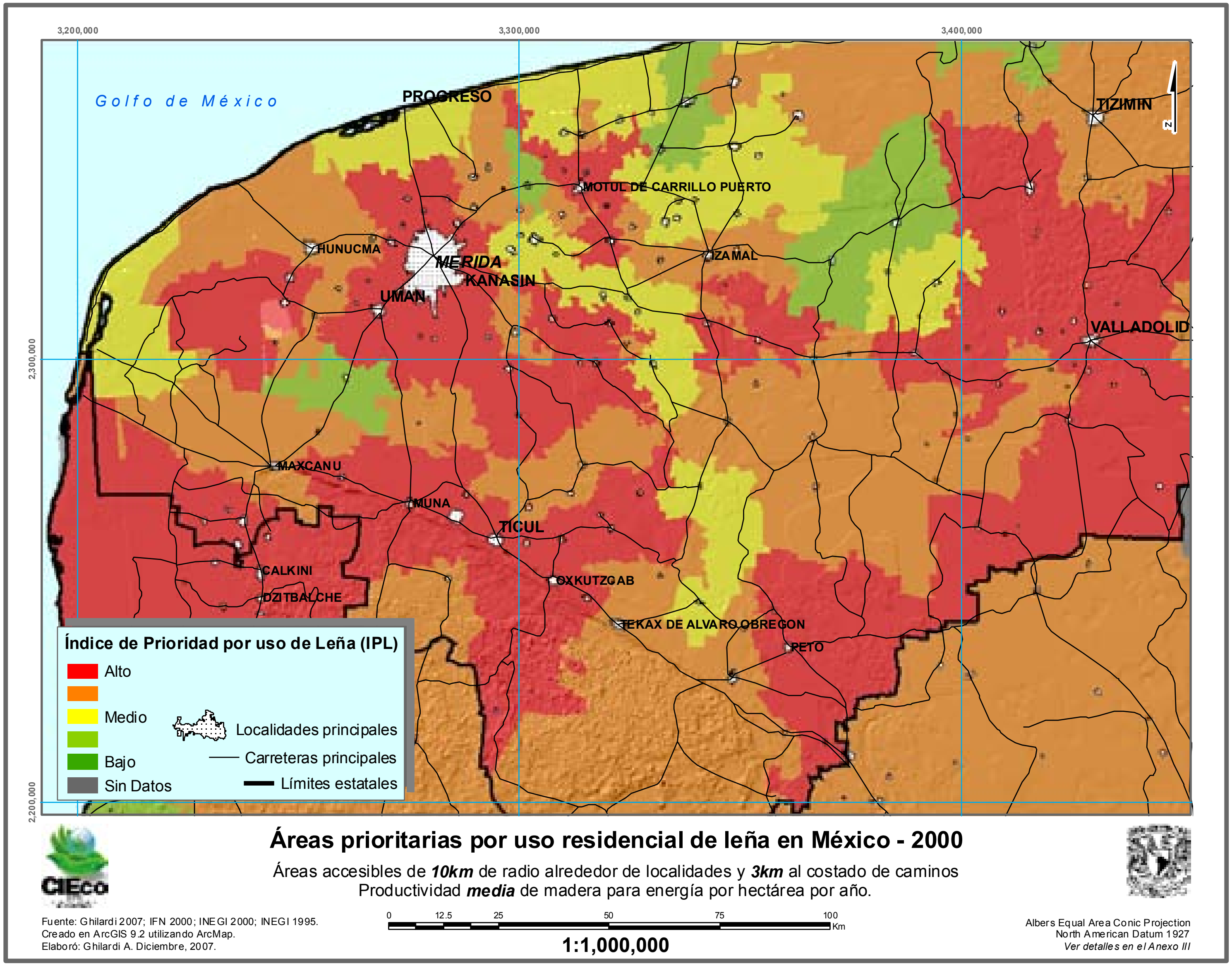
Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 12.5 25 50 75 100 Km

1:1,000,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.23. Área crítica Nº7: centro-oeste del Estado de Yucatán.



Áreas prioritarias por uso residencial de leña en México - 2000

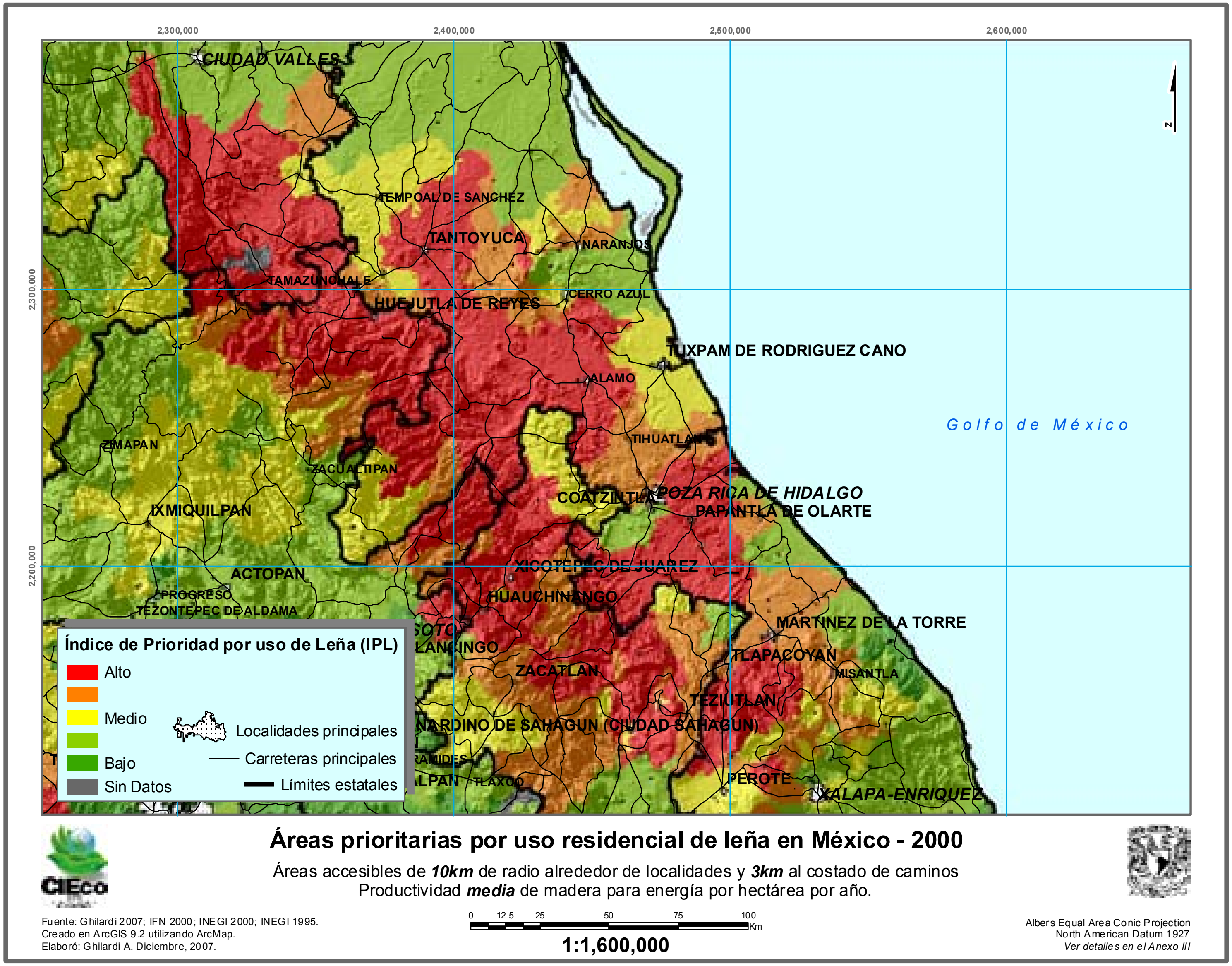
Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

1:1,000,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.24. Áreas críticas Nº1 y Nº2: huasteca Potosina-Veracruza y sierra norte de Puebla.



Áreas prioritarias por uso residencial de leña en México - 2000

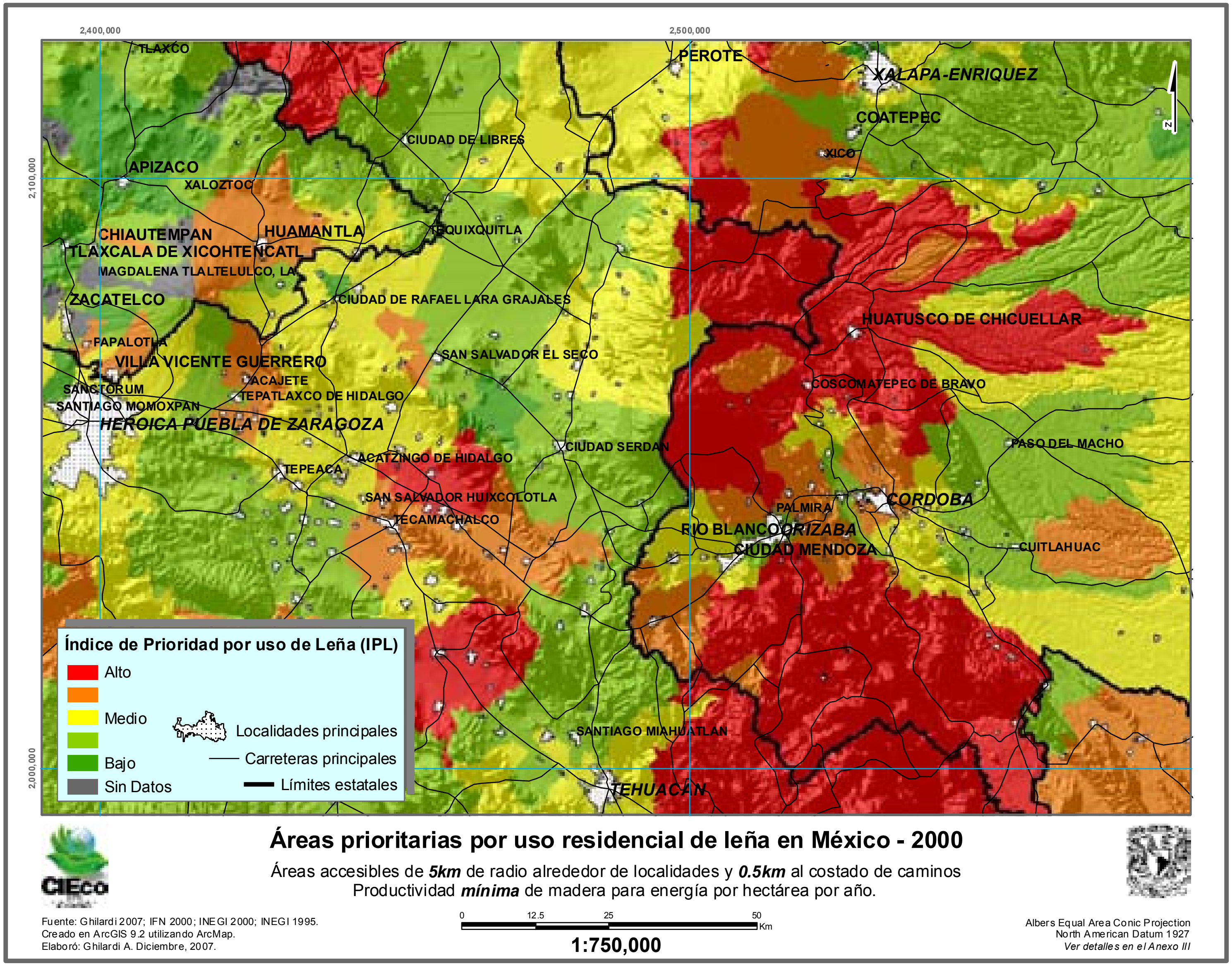
Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

1:1,600,000

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.25. Áreas crítica Nº3 y Nº13: municipios al este y sur de las ciudades Puebla y Xalapa respectivamente.



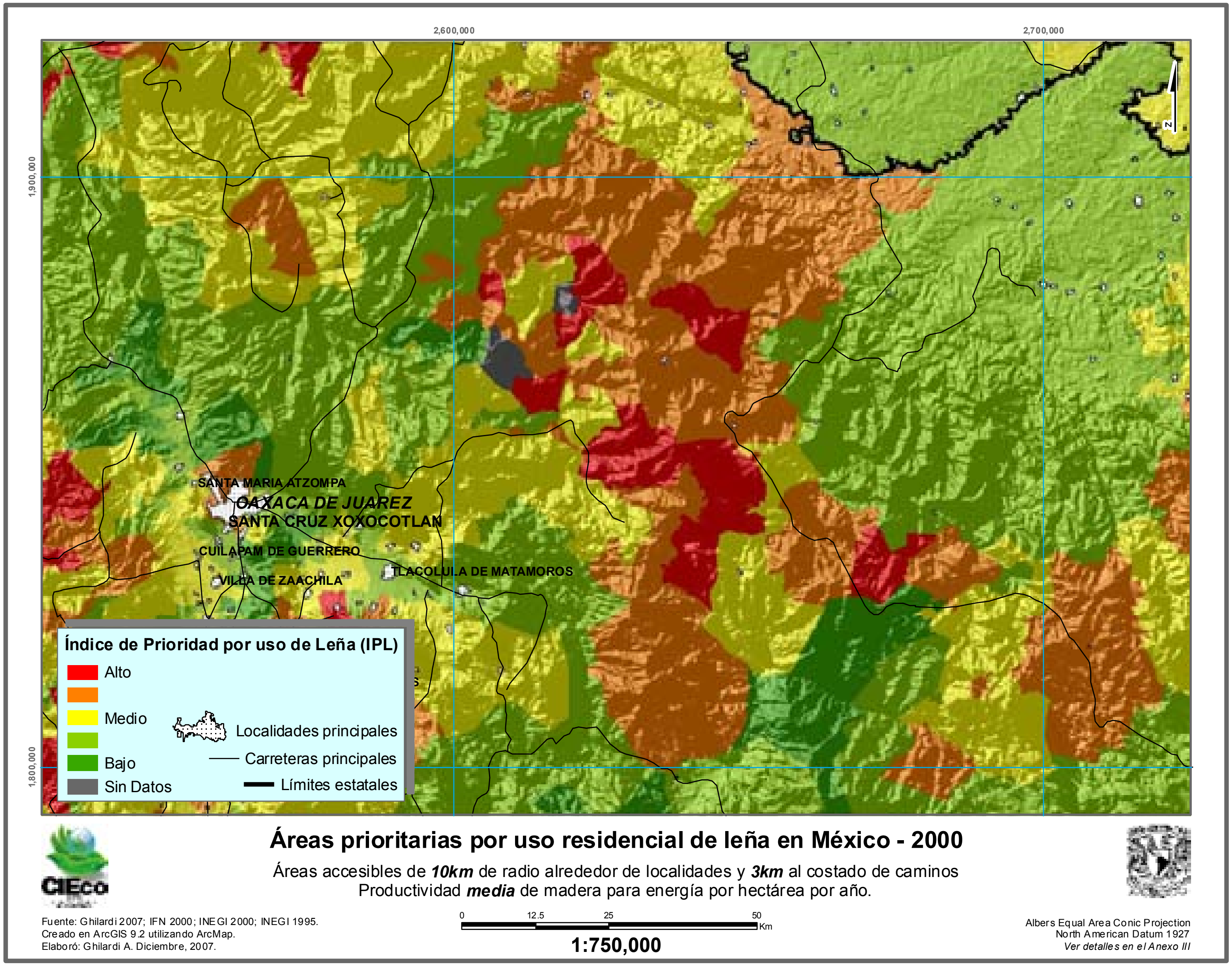
Áreas prioritarias por uso residencial de leña en México - 2000

Áreas accesibles de ***5km*** de radio alrededor de localidades y ***0.5km*** al costado de caminos
Productividad ***mínima*** de madera para energía por hectárea por año.

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.26. Área crítica Nº10: región Mixe en el Estado de Oaxaca.



Áreas prioritarias por uso residencial de leña en México - 2000

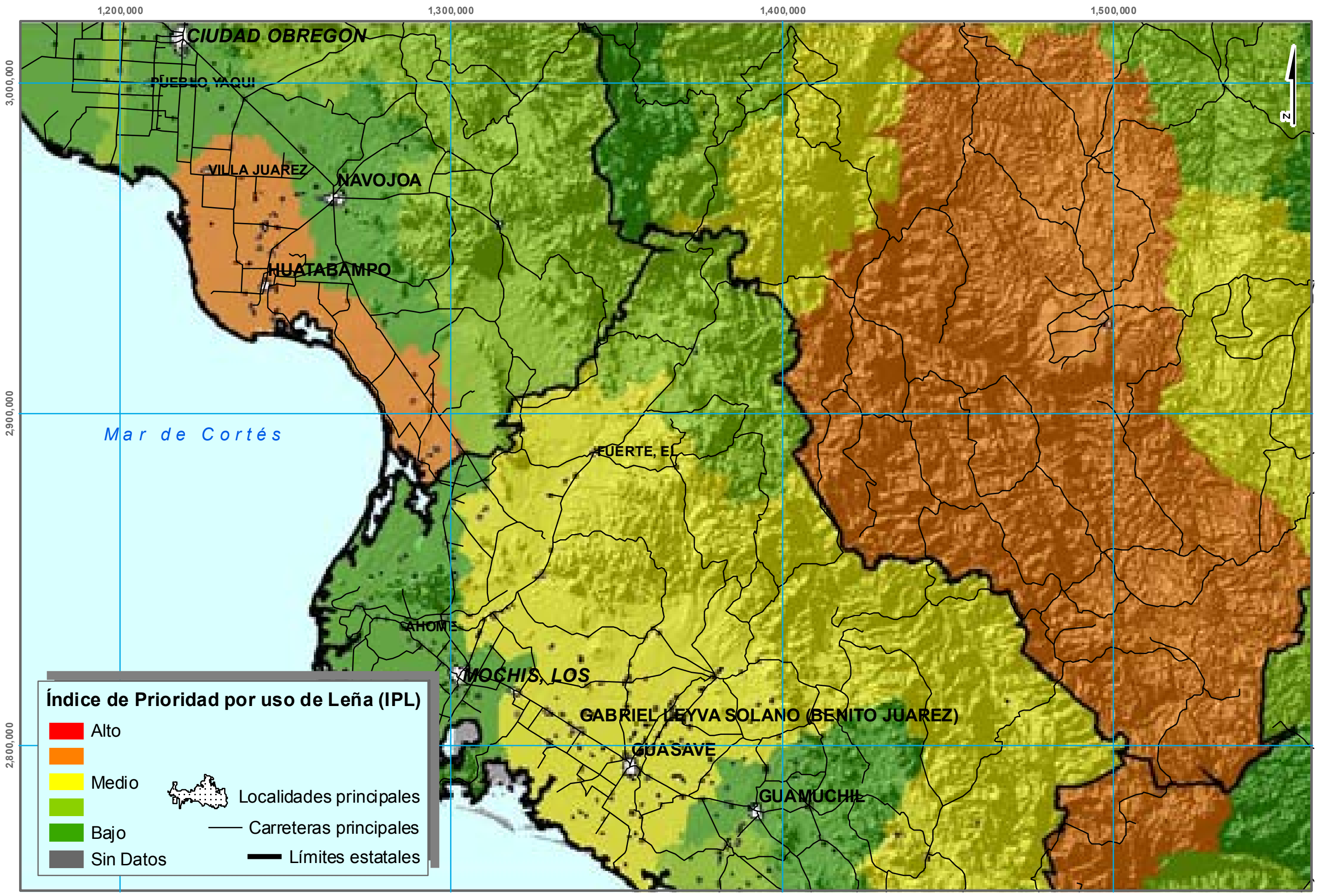
Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

1:750,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Figura III.27. Área crítica Nº18: Sierra Tarahumara.



Áreas prioritarias por uso residencial de leña en México - 2000

Áreas accesibles de ***10km*** de radio alrededor de localidades y ***3km*** al costado de caminos
Productividad ***media*** de madera para energía por hectárea por año.

Fuente: Ghilardi 2007; IFN 2000; INEGI 2000; INEGI 1995.
Creado en ArcGIS 9.2 utilizando ArcMap.
Elaboró: Ghilardi A. Diciembre, 2007.

0 12.5 25 50 75 100 Km

1:1,500,000

Albers Equal Area Conic Projection
North American Datum 1927
Ver detalles en el Anexo III

Tabla III.1. Promedios y desviaciones estándar de indicadores clave por municipio para las áreas críticas identificadas.

Cluster identification number	High Priority counties within cluster	Land cover change (1993-2000) (L_C) in t yr^{-1}		Fuelwood users (T) in number of users		Fuelwood users' density (D) in users ha^{-1}		Saturation (S_{AT}) in percentages		Fuelwood users' growth (1990-2000) (λ) (annual rate)		People belonging to an ethnic group (I) in percentages		Fuelwood balance (B) in t yr^{-1}	
1	33 (21 - 39)	-884	*176*	28,941	*3,512*	0.97	*0.08*	85%	*2%*	0.007	*0.001*	53%	*4%*	18,170	*4,634*
2	50 (38 - 59)	-66	*29*	18,074	*2,135*	1.43	*0.09*	80%	*2%*	0.008	*0.001*	49%	*4%*	2,562	*1,528*
3	14 (9 - 15)	194	*142*	16,222	*1,892*	1.23	*0.13*	82%	*3%*	0.017	*0.002*	2%	*1%*	6,212	*2,664*
4	49 (36 - 58)	-60	*28*	12,073	*1,537*	1.20	*0.10*	89%	*2%*	0.013	*0.001*	70%	*3%*	13,118	*2,906*
5	6 (2 - 9)	-116	*89*	29,184	*8,914*	1.11	*0.42*	68%	*7%*	0.016	*0.004*	33%	*10%*	29,007	*7,773*
6	4 (1 - 10)	4	*86*	57,247	*8,687*	0.56	*0.12*	43%	*4%*	0.025	*0.003*	3%	*2%*	78,722	*32,223*
7	25 (13 - 46)	-3,115	*552*	10,810	*1,443*	0.32	*0.04*	78%	*2%*	0.022	*0.001*	63%	*3%*	79,314	*17,777*
8	28 (12 - 44)	-1,816	*834*	27,544	*3,310*	0.72	*0.07*	83%	*2%*	0.012	*0.003*	48%	*4%*	99,424	*34,120*
9	6 (1 - 10)	-1,172	*411*	27,320	*3,663*	0.90	*0.16*	79%	*5%*	0.003	*0.002*	2%	*1%*	40,037	*14,762*
10	11 (7 - 19)	-175	*54*	5,440	*1,183*	0.65	*0.13*	94%	*2%*	0.004	*0.003*	84%	*1%*	28,034	*9,831*
11	21 (16 - 26)	-223	*75*	7,310	*1,410*	1.46	*0.46*	91%	*2%*	0.013	*0.003*	71%	*4%*	16,371	*4,927*
12	42 (21 - 62)	-639	*99*	19,151	*2,785*	0.50	*0.03*	89%	*2%*	0.012	*0.002*	59%	*4%*	48,635	*6,433*
13	2 (0 - 2)	-225	*184*	25,178	*4,361*	0.83	*0.17*	50%	*7%*	0.011	*0.005*	13%	*12%*	4,445	*8,153*
14	2 (0 - 8)	-4,367	*743*	46,825	*11,958*	0.26	*0.06*	61%	*9%*	0.018	*0.002*	1%	*0%*	254,558	*38,347*
15	10 (5 - 11)	-46	*147*	50,200	*12,096*	1.23	*0.13*	66%	*6%*	0.015	*0.003*	11%	*3%*	-9,027	*11,765*
16	1 (0 - 2)	-120	*118*	21,427	*465*	0.63	*0.02*	66%	*11%*	0.006	*0.000*	43%	*6%*	22,345	*3,346*

Tabla III.2. Promedios y desviaciones estándar de indicadores clave por municipio para las áreas críticas identificadas.

Cluster identification number	High Priority counties within cluster	INEGI welfare index		Fuelwood consumption in t yr^{-1}		Fuelwood supply in t yr^{-1}		Net CO$_2$ emissions in tCO$_2$ yr^{-1}		Total population		Ratio between rural/urban population	
1	33 (21 - 39)	1.85	*0.10*	30,054	*3,733*	48,224	*6,595*	4,553	*2,403*	29,485	*4,291*	4.694	*0.566*
2	50 (38 - 59)	1.81	*0.14*	16,128	*2,062*	18,690	*3,244*	3,319	*785*	23,098	*3,801*	2.665	*0.405*
3	14 (9 - 15)	1.53	*0.13*	15,169	*1,575*	21,381	*2,625*	1,697	*1,142*	16,406	*2,301*	2.634	*0.282*
4	49 (36 - 58)	1.47	*0.12*	10,731	*1,474*	23,849	*3,950*	582	*185*	13,194	*2,599*	2.205	*0.261*
5	6 (2 - 9)	2.56	*0.44*	27,095	*9,074*	56,102	*13,662*	1,901	*1,261*	40,688	*14,559*	0.781	*0.182*
6	4 (1 - 10)	4.40	*0.48*	47,304	*7,471*	126,025	*36,856*	2,830	*2,172*	111,462	*17,886*	1.657	*0.254*
7	25 (13 - 46)	3.04	*0.19*	10,029	*1,390*	89,343	*18,947*	30	*30*	13,060	*2,087*	0.436	*0.102*
8	28 (12 - 44)	1.55	*0.16*	23,385	*3,187*	122,809	*36,647*	460	*266*	30,288	*4,188*	3.265	*0.600*
9	6 (1 - 10)	2.20	*0.25*	22,539	*3,112*	62,576	*16,250*	392	*392*	30,461	*5,315*	2.960	*0.822*
10	11 (7 - 19)	1.42	*0.12*	4,524	*1,114*	32,558	*10,869*	24	*21*	4,641	*1,012*	1.790	*0.256*
11	21 (16 - 26)	2.08	*0.09*	6,535	*1,351*	22,906	*6,179*	681	*303*	6,938	*1,598*	0.525	*0.159*
12	42 (21 - 62)	2.00	*0.16*	15,274	*2,172*	63,909	*7,806*	0	*0*	28,396	*11,611*	2.058	*0.229*
13	2 (0 - 2)	3.00	*0.00*	19,082	*1,839*	23,527	*9,992*	3,400	*3,400*	40,472	*1,823*	0.500	*0.180*
14	2 (0 - 8)	2.75	*0.67*	36,576	*9,371*	291,134	*34,352*	0	*0*	130,299	*84,804*	2.231	*0.782*
15	10 (5 - 11)	2.55	*0.28*	52,531	*13,707*	43,504	*7,456*	34,076	*15,774*	69,975	*15,826*	4.630	*1.965*
16	1 (0 - 2)	2.50	*0.50*	20,880	*2,377*	43,225	*970*	0	*0*	26,966	*3,745*	0.500	*0.190*

IV. ANÁLISIS MULTI-ESCALAR DE LOS PATRONES ESPACIALES DE OFERTA Y DEMANDA DE LEÑA PARA USO RESIDENCIAL EN MÉXICO

IV.1 Multi-scale analysis of residential fuelwood supply and demand spatial patterns in Mexico

A continuación se adjunta el artículo sometido a la revista *Journal of Environmental Management*, actualmente bajo revisión por los editores de la revista.[15]

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[15] Para obtener una copia en formato PDF del artículo favor de contactarse con aghilardi@oikos.unam.mx.

Multi-scale analysis of residential fuelwood supply and demand spatial patterns in 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. So far, no methodologies have been developed for assessing these impacts while dealing with the site specificity of fuelwood use patterns and the scale dependency in supply and demand relationships. National or aggregated results may hide or even mislead the spatial distribution of critical situations, while local case studies do not show the overall picture. 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/or actions on local critical situations, starting from a national wide perspective and 2) estimating, at any one scale, the proportion of non-renewable harvested fuelwood, a key value for GHG emissions inventories (national scale) and for deriving Clean Development Mechanism (CDM) baselines for non-renewable fuelwood consumption in business as usual (BAU) scenarios (regional and local scales). 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. Twenty localities, out of a total of 90, were identified as high priority or critical in terms of six key indicators: number and density of fuelwood users; percentage of households using fuelwood; land cover change trends; balance between supply and demand; and percentage of ethnic population as a proxy variable of the resilience of consumption. We finally assessed the scale

dependency of the analysis by comparing key indicators from the national assessment and this more detailed study.

Keywords: Residential fuelwood use; Non-renewable biomass; Spatial analysis and modeling, Geographic information systems; Wood energy planning; WISDOM methodology; GHG emissions, Clean Development Mechanism (CDM), Mexico.

1. Introduction

About 2.5 billion people in developing countries relies on traditional and low tech uses of biomass[16] to meet their residential energy needs, predominantly cooking (IEA, 2006). On current trends, this number will increase to 2.7 billion by 2030 (IEA, 2006). Global fuelwood consumption in 2000 reached 2.3 billion m^3; accounting for roughly 60% of all the wood harvested that year. For the group of developing countries this proportion rises to 80% (Trossero, 2002). Thus, 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 (Kirschbaum, 2003; Righelato and Spracklen, 2007; Stupak et al., 2007; Tilman et al., 2006); including the residential sector of developing countries (Ghilardi et al., 2007; Masera et al., 2006). 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 fuel collection, b) increasing fuelwood prices and c) under extreme conditions, putting into risk a basic human need, such as food (Arnold et al., 2006; IEA, 2006).
- 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 (Arnold et al., 2003). Moreover, wood

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[16] Woodfuels (i.e. fuelwood and charcoal) are the dominant forms of traditional biomass energy, although given the current state of global data it's still difficult to accurately distinguish wood from other forms of biomass, such as agricultural waste and animal dung; even more on those countries were agricultural residues are an important fuel (e.g. China).

removal for fuel only at a low but constant rate may have negative impacts on the structure of natural forests (Rüdger, 2006).

- 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 CO2 emissions (Bailis et al., 2003; Bond et al., 2004).

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. In other words, deficit situations that severely affect woodfuel users and/or negatively impact natural forests vary from place to place (Arnold et al., 2006; Mahapatra and Mitchell, 1999; Top et al., 2004). 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 WISDOM[17] 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) (Masera et al., 2003; Masera et al., 2006). 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 hotspots, basic spatial units (BSU) 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 (Ghilardi et al., 2007); East Africa (Drigo, 2007a); South-east Asia (Drigo, 2007b); Brazil (Ghilardi, 2007); Senegal (Drigo, 2004a); and Slovenia (Drigo, 2004b). 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 locality level, which are necessary for directing concrete actions. Even in hot spots with an overall negative fuelwood demand/supply balance for example, not all localities face fuelwood scarcity, and similarly, regions with an overall positive balance may include deficit localities.

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 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, at any one scale, the proportion of non-renewable harvested fuelwood, a key value for GHG emissions inventories (national scale) and for deriving Clean Development Mechanism (CDM) baselines for non-renewable fuelwood consumption in business as usual (BAU) scenarios (regional and local scales).

In this article, a regional-based WISDOM methodology, at a sub-county level of analysis, was applied to the *Purhepecha* Region in central Mexico, a fuelwood hot spot previously identified in the national assessment (Ghilardi et al., 2007), and chosen for being a widely studied area in terms of fuelwood extraction and use patterns. For congruence and continuity, almost the same objectives as in the national assessment were defined: (1) identify at a sub-county level of analysis fuelwood hot spots in terms of residential fuelwood use and availability of fuelwood resources for the year 2000, and (2) estimate the fraction of fuelwood extracted on a non-renewable basis by the residential sector for the same year. Hot spots 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 forests. The same set of indicators used in the national assessment was selected. Finally, the results are compared with the previous WISDOM national assessment.

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[17] Woodfuels Integrated Supply/Demand Overview Mapping. For a complete description of the methodology and for more details about its practical implementation, existing databases, and other relevant information please refer to Masera *et al*. (2006).

2. Fuelwood extraction and use patterns in the study area

Situated within the state of Michoacan, in central Mexico, the *Purhepecha*[18] 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).

Fuelwood use in the *Purhepecha* Region is characterized by its spatial heterogeneity, and the widespread use of low-tech devices such as three stone fires for cooking. 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).

By the year 2000, total population reached 732 594 inhabitants, distributed over 149 420 houses, 787 localities (745 villages and 42 cities)[19] and 19 counties (INEGI, 2000). The number of exclusive fuelwood users was 227 701 in 2000, more than 30% of the total population.[20] Only 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 (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 exclusively for self consumption, while men using pack animals collect fuelwood either for self consumption or for selling in local markets. Men harvest living trees with axes or chainsaws, cut them into pieces in situ and carried

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[18] *Purhepechas* are the dominant ethnic group in the region, accounting for 14 % of total population.
[19] The Mexican Statistics Bureau (INEGI) set the threshold between rural and urban localities in 2 500 inhabitants.

out with the help of pack animals and eventually with motorized vehicles. Up to 3 or 4 hours (round trip) are spent by day for collecting fuelwood by any of the three types of gatherers. Most fuelwood comes from forest areas and abandoned farming plots under re-growth. Oaks are the preferred species for fuelwood given the characteristics of their wood.

3. Methods

Conducting a WISDOM analysis involves four steps (Masera et al., 2006): 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 thou, 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 patterns 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 use 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 sub-national administrative level of territorial division (e.g. counties or municipalities) is mostly chosen (Drigo, 2004a, 2004b, 2007a, 2007b; Ghilardi, 2007; Ghilardi et al., 2007). For a more detailed analysis focused only on a fuelwood hot spot 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 geo-referenced databases exist at this detailed level of administrative territorial division. Thus, non-administrative BSUs were selected instead of administrative ones.

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[20] The Mexican National Bureau of Statistics (INEGI) reports only exclusive fuelwood users. The mixed to exclusive fuelwood users ratio in the *Purhepecha* Region was estimated in 0.25 ± 0.10, using local surveys where exclusive and mixed users are reported vs. INEGI census data for the same localities, where only exclusive users are reported.

Non-administrative BSUs were defined by estimating accessible 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 woodfuel-shed, given means of transport and daily time available for collecting and transporting fuelwood.

When considering walking fuelwood gatherers, accessible areas or woodfuel-sheds were estimated based on a so called cost-distance map. In this map, each pixel or cell expresses the time needed for a walking person to walk through it.[21] Walking speeds were calculated as the product of a friction variable: terrain slope; an attraction variable: distribution and extent of preferred species, i.e. oak forest patches; barriers: lakes and rivers; and passages: bridges, tunnels and dams (Table 1). The cost-distance map was used to calculate the cumulative cost of moving away in each/any direction from a starting point, i.e. locality of origin. Time limits for walking fuelwood gatherers were set between 30 and 60 minutes one-way trip depending on the ratio between friction/attraction displacements velocities. For example, if no oak forests exist, walking fuelwood gatherers will be predisposed to walk as far as 30 minutes away from their localities of origin to search for fuelwood. On the contrary, if only oak forests surround the locality, walking fuelwood gatherers will be predisposed to walk as far as 60 minutes away from their localities of origin. In the middle of these two situations, when oak forest patches are found, fuelwood gatherers will be predispose to walk between 30 and 60 minutes depending on each patch crossed section longitude. Fuelwood gatherers never walk in a straight line from their localities to the outer perimeter of the accessible area. So, using 30-60 minutes as the time limit, a walking fuelwood gatherer may spend up to 3-4 hours (round trip) for harvesting fuelwood within the accessible area.

Fuelwood gatherers using motorized vehicles are much less influenced by slopes. However, vehicles can only travel through roads and paths. The roads and paths network was clipped within

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[21] For example, if a cell of 30x30 mts, has a value of one second per meter walked, then a walking person will spend 30 seconds to walk through this cell. If the next cell has a value of two seconds per meter walked, then a walking person will spend 60 seconds to cross this new cell. The GIS software calculates cost from cell center to cell center; therefore, the cost travel from one cell to the next is the sum of the cost of each multiplied by half the cell size. If the travel is diagonal, the distance is slightly longer (1.4 times the width or height), so the cost is increased accordingly by multiplying the cell size by 1.4.

a 5km radius buffers around each locality. Using the cost-distance map, accessible areas where then calculated at each side of roads and paths within a time limit between 10 and 20 min, assuming that people must get down from their vehicles and walk in order to look out for fuelwood.

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 (Masera et al., 2006; Top et al., 2004; Top et al., 2006). 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 included in the previous step (see 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:

$$FWS_v = \sum_{j=1}^{10} (A_{vj} * P_j) \qquad (1)$$

where FWS_v is the amount of fuelwood which can be sustainably harvested from each locality accessible area "v", in Mg yr^{-1} (dry matter); A_{vj} is each locality accessible area "v" by land cover "j" in ha and P_j is the fuelwood productivity by land cover class "j" in Mg ha^{-1} yr^{-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:

$$LCV_v = \sum_{k=1}^{210} \left(A_{vk} * \Delta P_k\right)/14 \qquad (2)$$

where LCV_v is the annual variation in fuelwood production per locality accessible area "v", in Mg yr^{-1} (dry matter), due to land cover changes that occurred between years 1986 and 2000 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} yr^{-1} (dry matter).

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 2); 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. Eighty-eight (88) ground georeferenced control points were used for ten land cover classes. A land cover change map (1986-2000) was also obtained.

The classification system was based on the Mexican National Forest Inventory 2000 (Palacio-Prieto et al., 2000). 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 2) were derived from the study by Ordoñez et al. (2008) 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.

$$P_j = \frac{B_j * 2 * Ff_j}{t_j} \qquad (3)$$

where Bj 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*2/tj correspond 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 measure in the *Purhepecha* Region by Berrueta et al. (2007) 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 yr^{-1} cap^{-1}) and mixed users 2.3 ± 1.1 Kg day^{-1} cap^{-1} (0.8 ± 0.4 Mg yr^{-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):

$$T_l = U_l + M_l \qquad (4)$$

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 (INEGI, 2000), while M was estimated using the following equation:

$$M_l = U_l * \beta \qquad (5)$$

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

$$D_v = (U_l + M_l * 0.68) / A_v \qquad (6)$$

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 (Berrueta et al., 2007).

$$S_l = F_l / H_l \qquad (7)$$

where Sl 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".

$$I_l = I_{Nl} / P_{Tl} \qquad (8)$$

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.

$$C_l = \left(U_l * FC + M_l * FCM\right) \qquad (9)$$

where C_l is the fuelwood consumption per locality “l”, in Mg yr^{-1} (dry matter); FC and FCM are the average per capita fuelwood consumption in the *Purhepecha* Region for exclusive and mixed users respectively in Mg yr^{-1} cap^{-1} (dry matter), 1.24 ± 0.06 and 0.84 ± 0.09 respectively. Uncertainty values correspond to the standard error (Berrueta et al., 2007).

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 yr^{-1} (dry matter).

3.5 Identification of fuelwood hot spots in the Purhepecha Region

In order to identify fuelwood hot spots at a sub-county level in the *Purhepecha* Region, a similar methodological approach described by Ghilardi et al. (2007) 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 accessible areas around localities in this case, instead of counties, as in the WISDOM national assessment. Localities’ accessible areas were analyzed by means of the selected and described indicators, and then ranked by using MCA techniques. Three sub-steps were followed (Geneletti, 2004; Ghilardi et al., 2007): 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- (Beinat, 1997; Geneletti, 2004). 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 B.

3.5.2 Weight assignment and aggregation procedure

Following Ghilardi et al. (2007) and Geneletti (2004), three different weight sets were assigned to indicators in order to include different perspectives into the priorization analysis (Table 3). 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 (Janssen, 2001), 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 "v" is given by the equation:

$$\mathrm{WSO}_{\mathrm{sv}} = \sum_{d=1}^{6} \mathrm{R}_{\mathrm{vd}} * \mathrm{W}_{\mathrm{ds}} \qquad (11)$$

where R is the standardized score per locality accessible area "v" 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 $\mathrm{WSO}_{\mathrm{sv}}$ 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 is 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):

$$\mathrm{PF}_v = B_v / \mathrm{F}_v \tag{12}$$

where PF_v is the annual rate of fuelwood extraction from forests on a non-renewable basis per locality accessible area "v", in Mg ha^{-1} yr^{-1} (dry matter) for $Bv<0$ and $\mathrm{PF}_v=0$ for $Bv\geq0$; and F_v is the forest area per locality accessible area "v", in ha (all land cover categories in table 2 account for forest areas, except for agriculture).

As seen in table 2, 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 fell 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:

$$\mathrm{Sto}_{vt} = \mathrm{Sto}_{vt0} * e^{kv\, t} \tag{13}$$

Where Sto_{vt} is fuelwood stock i.e. aboveground woody biomass suitable as fuelwood in forests per locality accessible area "v" in time "t"; Sto_{vt0} is fuelwood stock per locality accessible area “v” in time 0 (year 2000); and k_v is the depletion rate per locality accessible area “v”, as a constant proportion of remaining stock.

$$k_{vt} = \ln\left(\frac{\mathrm{Sto}_{vt1}}{\mathrm{Sto}_{vt0}}\right) \tag{14}$$

Where Sto_{vt1} is fuelwood stock per locality accessible area “v” 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).

$$t0.5_v = \frac{\ln\left(\frac{\mathrm{Sto}_{vt0} * 0.5}{\mathrm{Sto}_{vt0}}\right)}{k_v} = \frac{0.69}{k_v} \tag{15}$$

Where $t0.5_v$ is the time needed to deplete half of fuelwood stock per locality accessible area “v” in years.

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):

$$\mathrm{NRFW}_v = B_v / \mathrm{C}_1 \tag{16}$$

where NRFW_v is the fraction of fuelwood consumption extracted on a non-renewable basis per locality accessible area “v”, as a ratio or percentage for $Bv<0$ and $NRFWv=0$ for $Bv\geq 0$.

3.8 Uncertainty in basic data inputs

Although WISDOM is meant to provide relative/qualitative values rather than absolute/quantitative data, incorporating uncertainties in the analysis permitted to quantify key variables as fuelwood balance and NRFW. See Appendix C 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 (Ordoñez et al., 2008) (see notes on table 2); 2) time needed to reach aboveground biomass stock in years (see notes on table 2); 3) fuelwood per capita consumption for exclusive and mixed users (Berrueta et al., 2007). Standard error values were calculated from reported statistical parameters: $n=23$, $M=3.4$, $SD=0.8$, Student's $p<0.05$ for exclusive users; and $n=20$, $M=2.3$, $SD=1.1$, 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.

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 so 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). Figure 2 shows an example of a 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 an 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.[22]

4.2 Fuelwood hot spots in the Purhepecha Region

Following a similar approach and index calculation as the one used in the national assessment (Ghilardi et al., 2007), the newly identified BSUs were assessed by means of each indicator and ranked following the Fuelwood Priority Index (FPI). Figures 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

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[22] Preliminary field data gathered by means of GPS receptors for showed that extraction sites lie within estimated accessible areas for walking fuelwood gatherers.

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 figures 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 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 in 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 figure 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 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

Figure 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 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 9 600 ha in the Region. About 1 000 ha lye 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 figure 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.

Oak forest patches lying within areas only accessible to fuelwood gatherers using motorized vehicles (arrows in figure 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 have 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)

Table 4 shows both the balance and NRFW estimates for the *Purhepecha* Region and for the top 10 scoring localities and NLCs. While fuelwood balance (equation 10) gives the overall amount of fuelwood extracted on a non-renewable basis from woodfuel-sheds. 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 CO2 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 CO2eq 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. Table 4 shows that of both approaches are equally wrong as the quantification of renewability aimed at locality-based carbon offset projects must be conducted on a locality by locality basis, if misleading estimates are to be avoided.[23]

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 which overall aggregated estimates render positive for the case of balance or fully renewable for the case of NRFW. Based on the Region total values shown in table 4, all localities in the *Purhepecha* Region should be assigned a 0-25% NRFW, when this is clearly a false or misleading value when considering individual estimates of selected localities that extract their fuelwood on a non-renewable basis, and where carbon offset project should reasonably be implemented. Note moreover from figure 5 how wide variations in estimates occur even among adjacent or neighbor localities.[24]

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 (Ghilardi et al., 2007), gives 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) in the national assessment all localities with at least 20 households relying of fuelwood were included;[25] so, the present analysis was run again including this new set of localities; 3) in order

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[23] The use of GIS along with automate sub-routines, i.e. each loop recruiting a single locality, have proven particularly useful for the present analysis (Scheme 1).

[24] 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.* (2006). 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 (CDM, 2006).

[25] Notice that 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

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. (2007).

Table 5 shows key indicators aggregated for the Purehepecha Region as compared with the WISDOM national assessment (Ghilardi et al., 2007). 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 CO2 emissions from non-renewable fuelwood use by the residential sector were shown disaggregated by county, and from this information, a national estimate of GHG emissions was drawn. As seen by results from table 5, 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.

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average value for each indicator. This is to say, results from the national assessment are spatially indivisible beyond the county level, namely the BSU.

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.

5. Conclusions and future research directions

Starting from a national wide perspective, Mexican counties were ranked based on the number, density and annual growth rate of fuelwood users; the percentage of households that use fuelwood; the resilience of fuelwood consumption; and the magnitude and likely trends of fuelwood resources. The analysis allowed the identification of 304 high priority counties (HPCs), which showed a spatially aggregated pattern into 16 clusters or county-based fuelwood hot spots (Ghilardi et al., 2007). Following a similar approach over one hot spot previously identified and accounting for 19 of the 304 HPCs, 20 localities, out of a total of 90 in the study region, were identified 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 permits 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 however that locality-based fuelwood hot spots are not an array of isolated localities unrelated among each other. On the contrary, each locality's fuelwood supply and demand patterns are linked to other localities through local trade, cultural relationships, informal territorial agreements, roads networks, among others. Trade offs may 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 (Masera et al., 2000), 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 an hypothetical detailed analysis, which will require hardly available inputs and an impressive computing capacity.

6. Theory and calculation

Appendix A: Workflow of model.

Scheme 1 shows a simplified representation of the workflow of the WISDOM grid-based model developed for the present study for analyzing fuelwood supply/demand spatial patterns at a sub-county level.

Appendix B: Standardization of indicators (linear value functions).

Graphics 1 and 2 show linear value functions for four of the six indicators used in the construction of the FPI, considering accessible areas for walking fuelwood gatherers and fuelwood gatherers using motorized vehicles respectively. Saturation and ethnicity were not included as real values of these indicators 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 and 1 (Y axis). Break points were set to avoid non representative value functions due to wide ranges in indicators' real values.

Appendix C. Error propagation equations.

Standard error values from input data were propagated through the following equations (Δ represent the standard error):

$$\Delta \mathrm{P_j} = \sqrt{\left(\frac{\Delta \mathrm{B_j} * 2 * \mathrm{Ff_j}}{\mathrm{B_j} * 2 * \mathrm{Ff_j}}\right)^2 + \left(\frac{\Delta t_\mathrm{j}}{\mathrm{t_j}}\right)^2} * \left(\frac{\mathrm{B_j} * 2 * \mathrm{Ff_j}}{t_j}\right) \tag{17}$$

where P_j is the fuelwood productivity by land cover class "j" in Mg ha^{-1} yr^{-1} (dry matter); 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 (woody 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.

$$\Delta \mathrm{FWS_v} = \sqrt{\sum_{j=1}^{8} \left(\mathrm{A_{vj}} * \Delta \mathrm{P_j}\right)^2} \tag{18}$$

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

$$\Delta \mathrm{M_l} = \mathrm{U_l} * \Delta\beta \tag{19}$$

where U are exclusive fuelwood users per locality "l"; M are mixed users per locality "l" (people that use both fuelwood and LPG); and β is the mixed to exclusive fuelwood users ratio in the *Purhepecha* Region (0.25 ± 0.10).

$$\Delta \mathrm{C_l} = \sqrt{\left(\mathrm{U_l} * \Delta FC\right)^2 + \left(\sqrt{\left(\frac{\Delta \mathrm{M_l}}{M_l}\right)^2 + \left(\frac{\Delta FCM}{FCM}\right)^2} * (M_l * FCM)\right)^2} \tag{20}$$

where $\mathrm{C_l}$ is the fuelwood consumption per locality "l", in Mg $\mathrm{yr^{-1}}$ (dry matter); FC and FCM are the average per capita fuelwood consumption in the *Purhepecha* Region for exclusive and mixed users respectively in Mg $\mathrm{yr^{-1}}$ $\mathrm{cap^{-1}}$ (dry matter) (Berrueta et al., 2007).

$$\Delta \mathrm{B_v} = \sqrt{\left(\Delta \mathrm{FWS_v}\right)^2 + \left(\Delta \mathrm{C_l}\right)^2} \tag{21}$$

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

$$\Delta \mathrm{NRFW_v} = \sqrt{\left(\frac{\Delta B_v}{B_v}\right)^2 + \left(\frac{\Delta \mathrm{C_l}}{C_l}\right)^2} * \mathrm{NRFWv} \tag{22}$$

where $NRFW_v$ is the fraction of fuelwood consumption extracted on a non-renewable basis per locality accessible area "v", as a ratio or percentage for $Bv<0$ and $NRFW_v=0$ for $Bv\geq0$.

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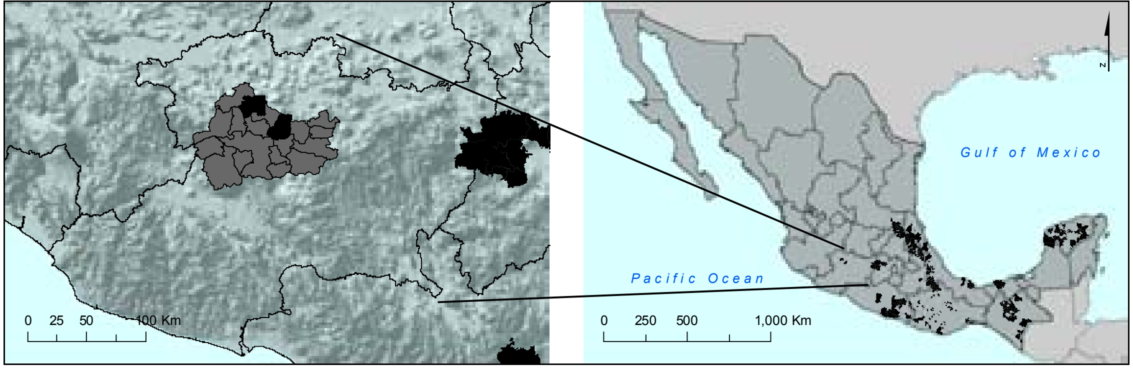
Figure 1. Study area: the *Purhepecha* Region.



Notes: Black irregular spots in both maps represent fuelwood high priority counties following WISDOM's national assessment (Ghilardi et al., 2007). On the map of the left, counties conforming the *Purhepecha* Region, in the north-west of *Michoacán* State, were highlighted in dark grey.

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

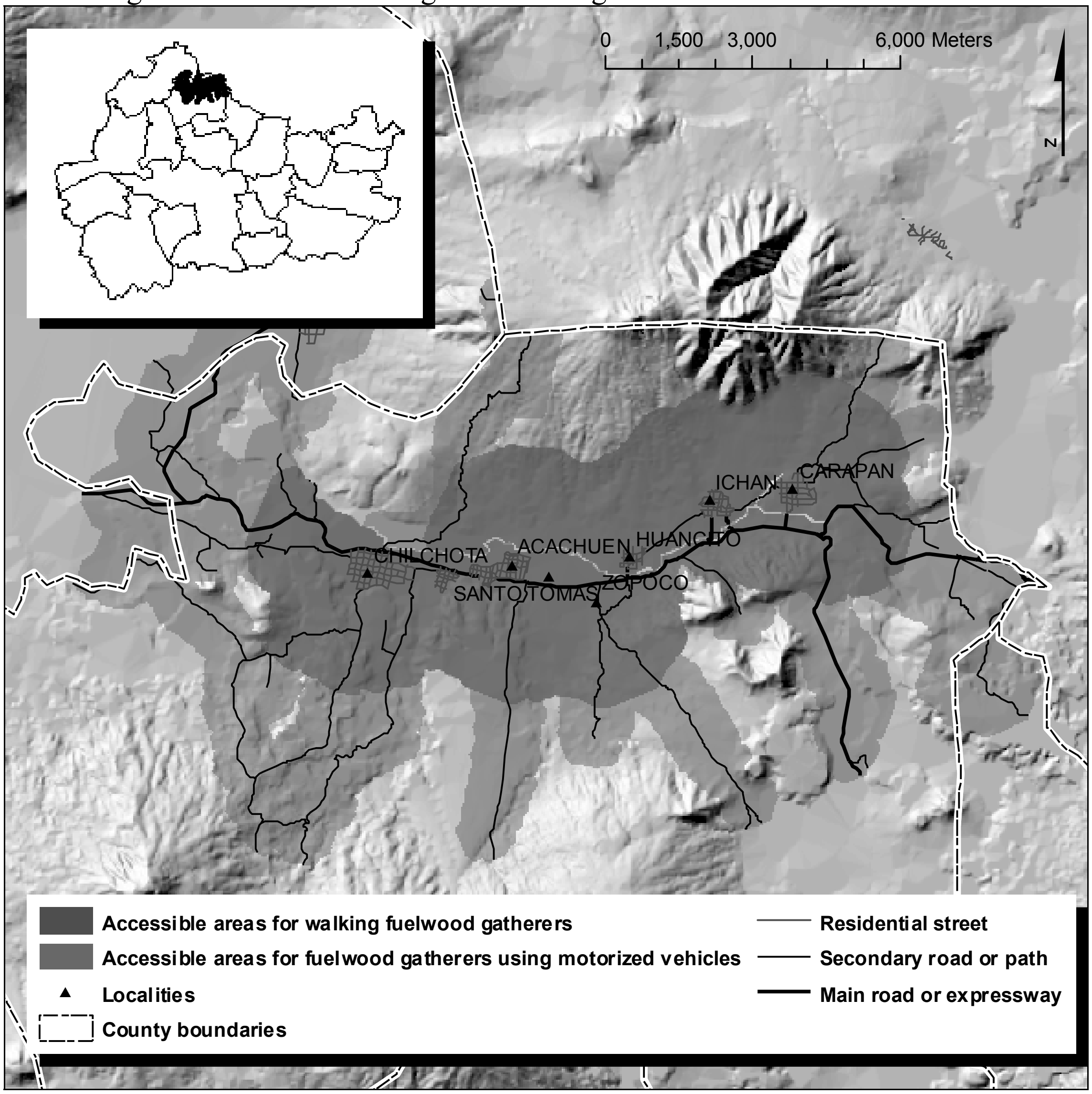
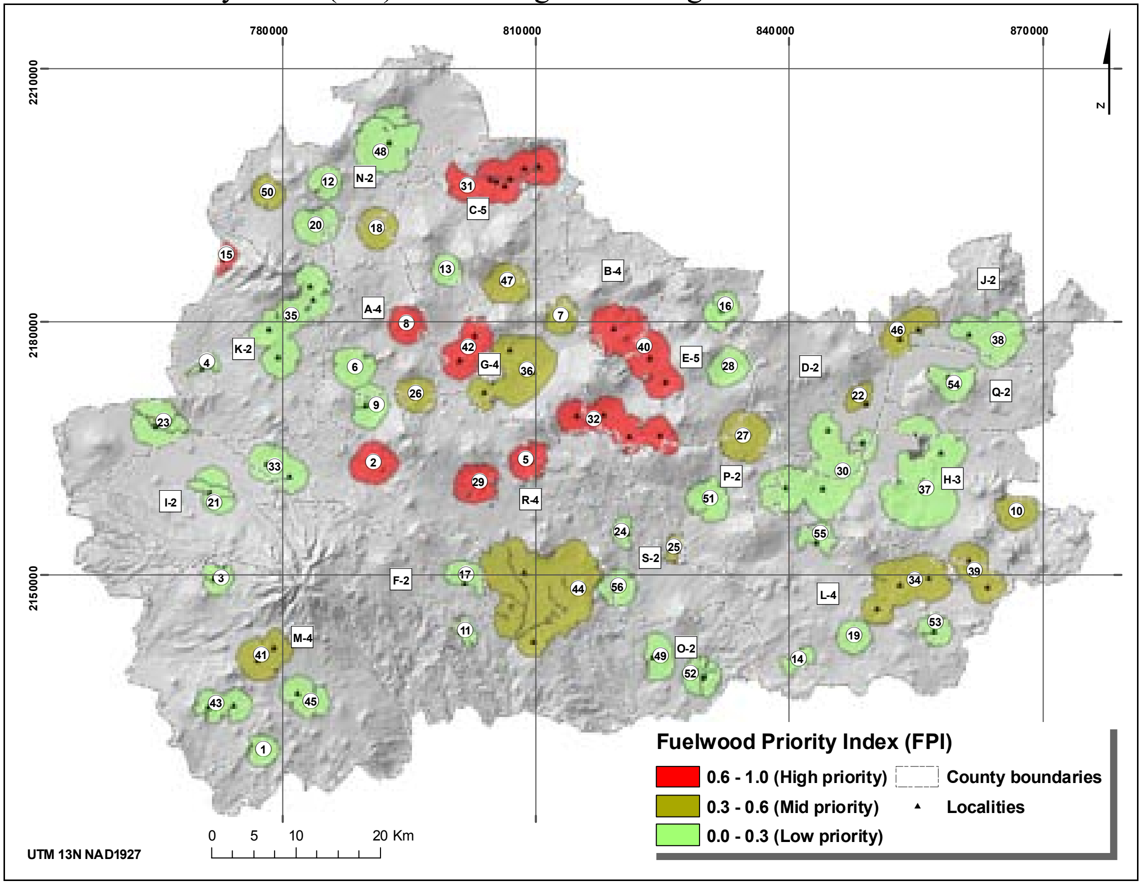
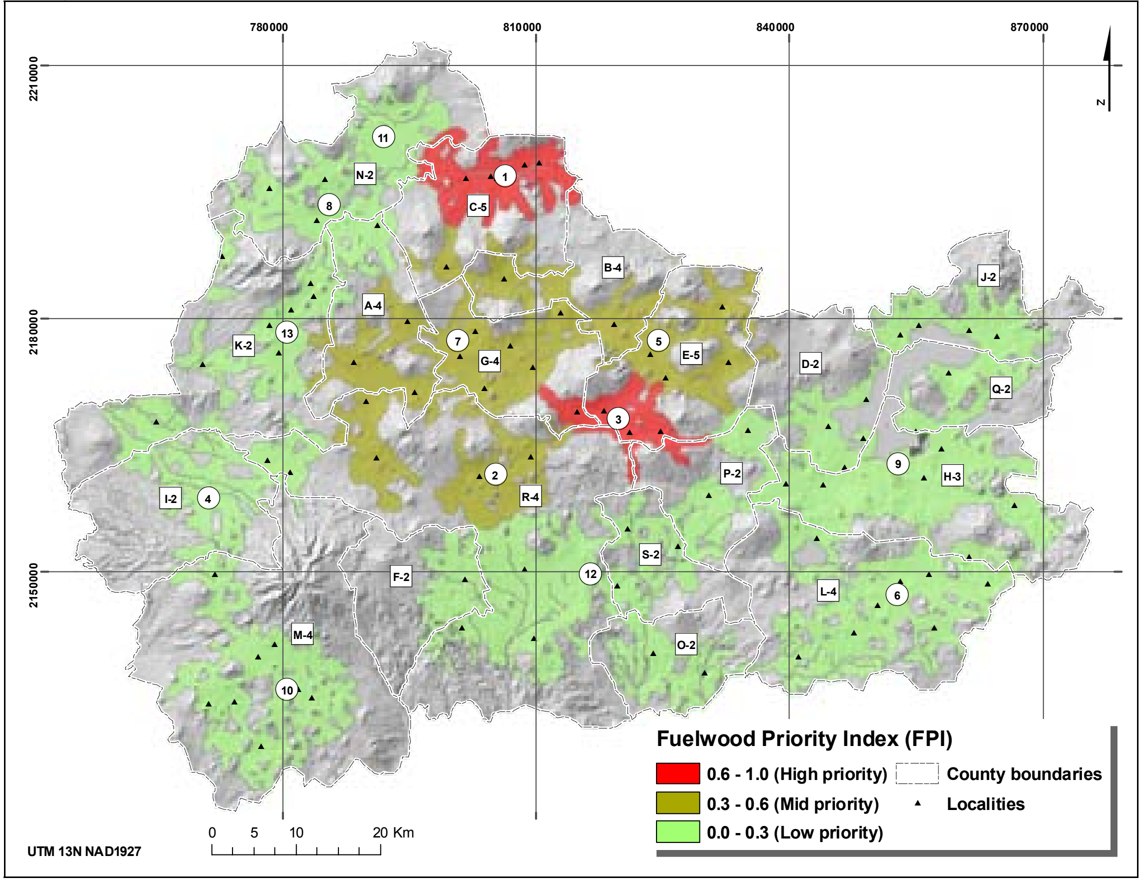


Figure 3. Priorization of single localities and Neighbor Localities Clusters (NLCs) based on the Fuelwood Priority Index (FPI) for walking fuelwood gatherers.



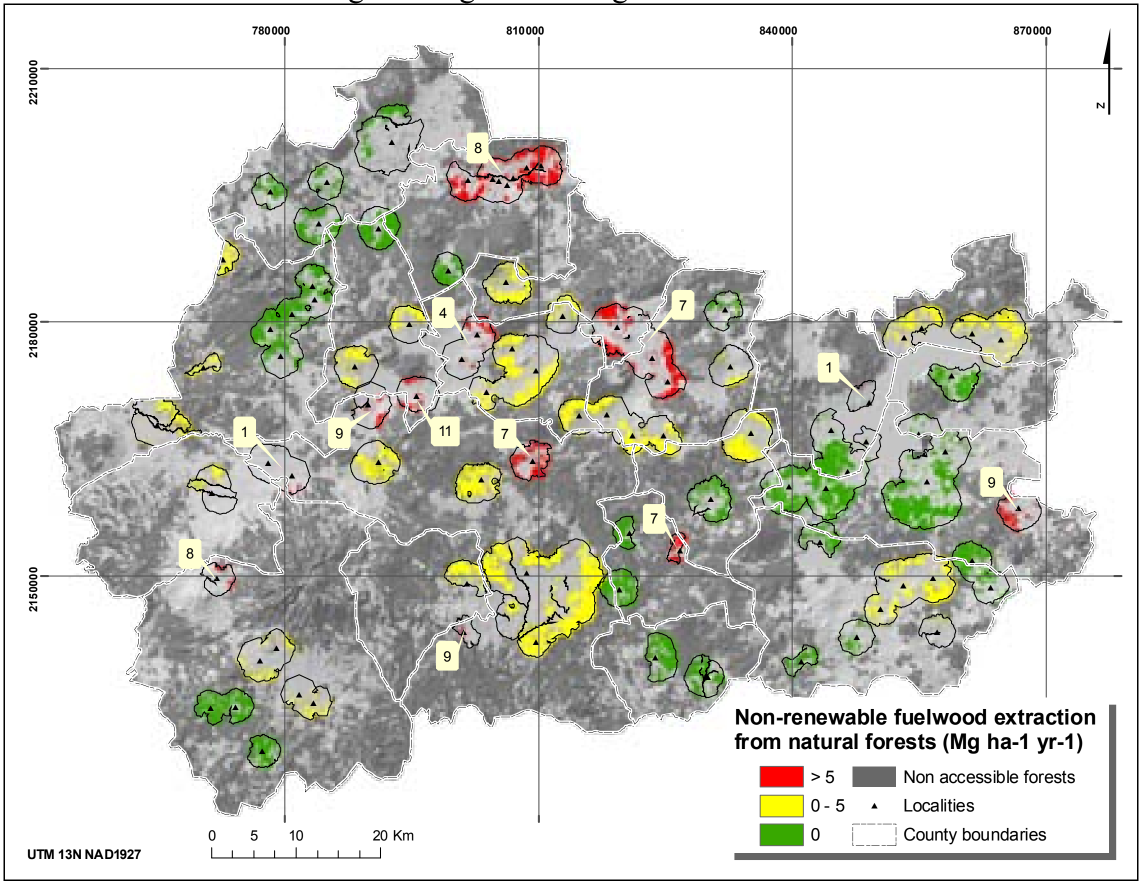
Notes: Squared letters and numbers correspond to the county name and the FPI from the national priorization respectively (Ghilardi et al., 2007). (A) *Charapan*; (B) *Cherán*; (C) *Chilchota*; (D) *Erongaricuaro*; (E) *Nahuatzen*; (F) S*an Juan Nuevo Parangaricutiro*; (G) *Paracho*; (H) *Pátzcuaro*; (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*.

Figure 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.



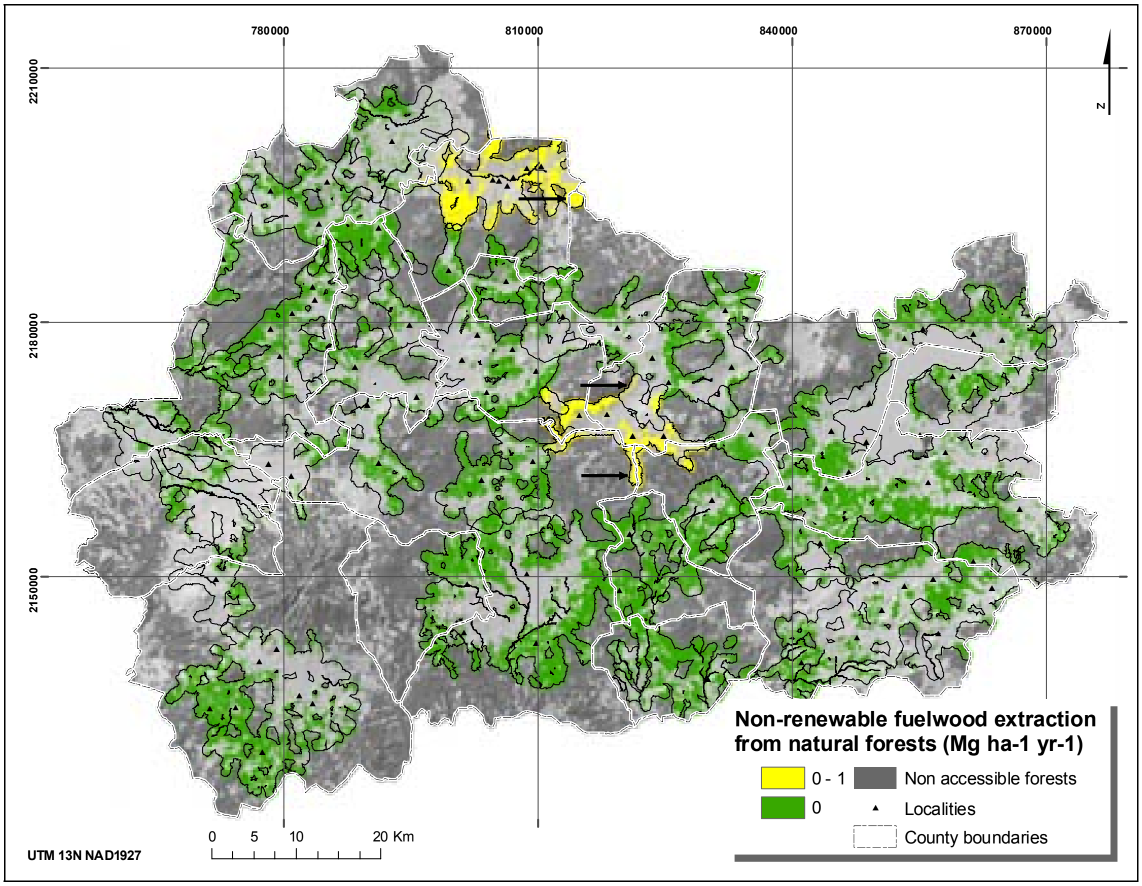
Notes: Squared letters and numbers correspond to the county name and the FPI from the national priorization respectively (Ghilardi et al., 2007). (A) *Charapan*; (B) *Cherán*; (C) *Chilchota*; (D) *Erongaricuaro*; (E) *Nahuatzen*; (F) San *Juan Nuevo Parangaricutiro*; (G) *Paracho*; (H) *Pátzcuaro*; (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*.

Figure 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.

Figure 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. Arrows show remanent oak forests patches only accessible to fuelwood gatherers using motorized vehicles . (1) *NLC_Cañada* = 0.74 Mg ha^{-1} yr^{-1}; (3) *NLC_Comachuén* = 0.90 Mg ha^{-1} yr^{-1}. Expected time for depletion of half the fuelwood stock available from forest areas exceed 70 years in both cases.

Table 1. Displacement velocities of walking fuelwood gatherers according to slope angles, attractive land covers, barriers and passages.

Slope range in degrees	Displacement velocity in seconds spent per meter walked		
	All land cover classes except oak forest and their attractiveness buffer areas	Oak forests	Oak forests' attractiveness buffer areas.
0.0º - 8.5º	0.8	0.4	0.6
8.5º - 16.7º	1.2	0.6	0.9
16.7º - 24.2º	2.1	1.05	1.575
24.2º - 35.0º	4.5	2.25	3.375
35.0º - 45.0º	9	4.5	6.75
45.0º - 90.0º	∞	∞	∞
Bridges	0.8	0.8	0.8
Tunnels	0.8	0.8	0.8
Dams	0.8	0.8	0.8
Rivers	∞	∞	∞
Lakes	∞	∞	∞

Source: Puentes (2002) and own estimates made from field surveys over the *Purhepecha* Region.

Table 2. 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} yr^{-1} (c)	MAI as a percentage of aboveground biomass stock	Fuelwood to aboveground biomass ratio (Ff) (d)	Fuelwood increment in Mg ha^{-1} yr^{-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. (2008). 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 (Drigo, 2007a). 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 (Ordoñez et al., 2008). (b) (†) average age of trees outside forests from unpublished own field-based estimates in the *Purhepecha* Region; (*) Pine-Oak forests / 2; (‡) (NFI, 1994); (**) (Bonfil, 2006); (††) average between Pine and Oak forests; (‡‡) (Návar et al., 2001). A 25% uncertainty was assumed for all land cover classes. (c) MAI = (a) / (b). (d) Ff correspond 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 (Brown, 1997; Brown et al., 1989; Brown and Lugo, 1982; Cannell, 1984, 1985). 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 is 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 appendix C).

Table 3. Indicators used in the construction of the FPI and weights assignments.

Indicator	Abrev.	Equation	Unit	Module of origin	Weight Set 1	Weight Set 2	Weight Set 3
Land cover change (1986-2000)	LCV_v	(2)	Mg yr^{-1}	Supply	0.17	0.03	0.23
FW users	T_l	(4)	number of users	Demand	0.17	0.03	0.23
FW density	D_v	(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	0.30	0.03
FW balance	B_v	(10)	Mg yr^{-1}	Integration	0.17	0.60	0.06
				Total	1.00	1.00	1.00

Table 4. 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 Mg yr-1	Confidence Interval
31	*NLC_Cañada**	-16.2 ± 2.5	-21.0 - -11.3
40	*NLC_Sevina**	-15.1 ± 1.7	-18.5 - -11.7
32	*NLC_Comachuén**	-9.1 ± 1.7	-12.5 - -5.8
5	*Capácuaro**	-7.2 ± 0.8	-8.7 - -5.6
34	*NLC_Opopeo*	-7.1 ± 1.5	-9.9 - -4.2
42	*NLC_Urapicho**	-5.4 ± 0.6	-6.5 - -4.3
10	*Cuanajo*	-3.5 ± 0.5	-4.5 - -2.5
2	*Angahuan**	-2.8 ± 0.7	-4.2 - -1.3
25	*San Ángel Zurumucapio*	-2.7 ± 0.3	-3.4 - -2.1
33	*NLC_Nuevo Zirosto*	-2.2 ± 0.2	-2.6 - -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 - -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 - 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 - 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**	83 ± 10	63 - 100
3	*Apo*	77 ± 10	57 - 97
5	*Capácuaro**	75 ± 10	55 - 95
40	*NLC_Sevina**	75 ± 10	55 - 95
25	*San Ángel Zurumucapio*	74 ± 10	54 - 94
31	*NLC_Cañada**	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**	

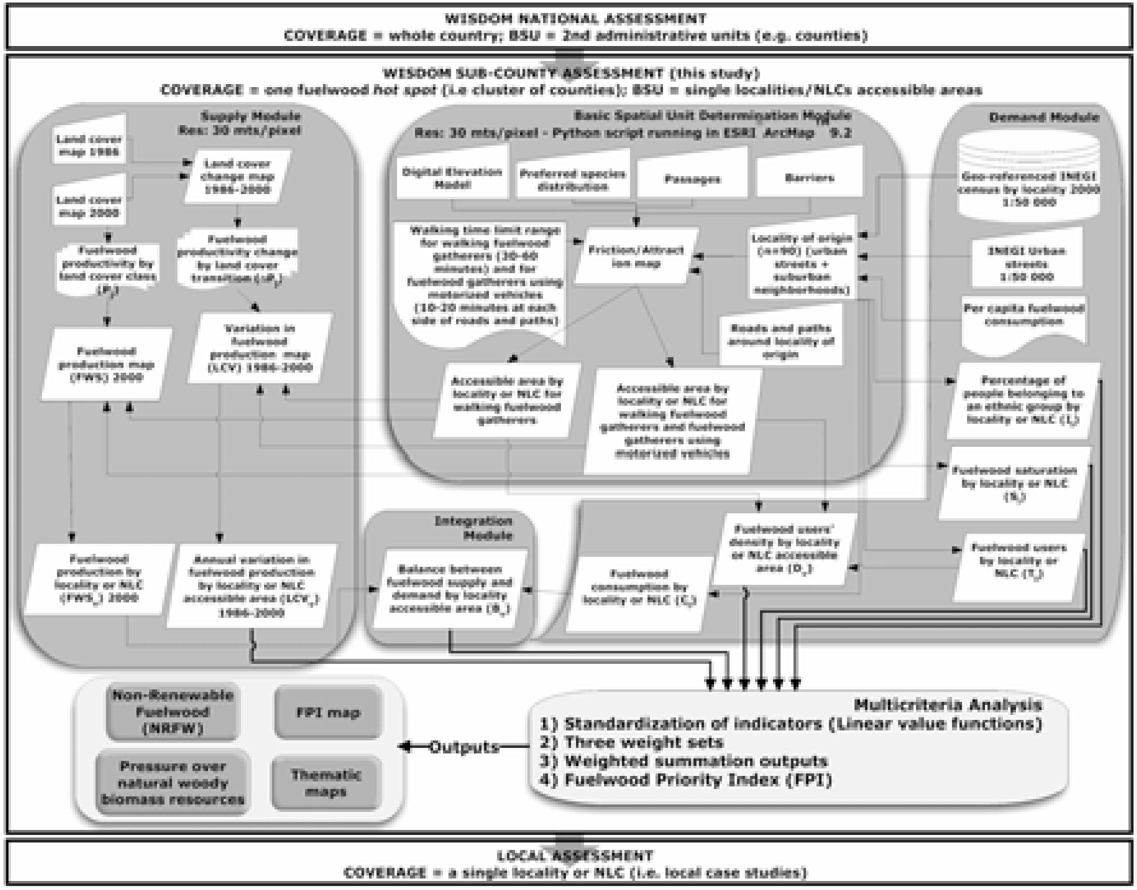
Notes: Uncertainty values correspond to propagated standard errors. Confidence intervals assuming an alpha significance level of 0.05 (z-value = 1.96). * ranked as high priority by the FPI (see section 4.2).

Table 5. Aggregated indicators for the 19 counties of the *Purhepecha* Region as compared with the previous WISDOM national assessment.

Indicator	National assessment		This study	
	Mean	Confidence interval†	Mean	Confidence interval‡
Accessible area in thousand of hectares	653	609 - 653	279	
Fuelwood supply (FWS) in Kt yr^{-1}	901	196 - 1 583	377	242 - 511
Fuelwood users (T) in thousand of users	270	216 - 324	270	228 - 312
Fuelwood consumption (C) in Kt yr^{-1}	253	169 - 352	314	267 - 359
Fuelwood balance (B) in Kt yr^{-1}	647	-156 - 1 415	64	-78 - 206

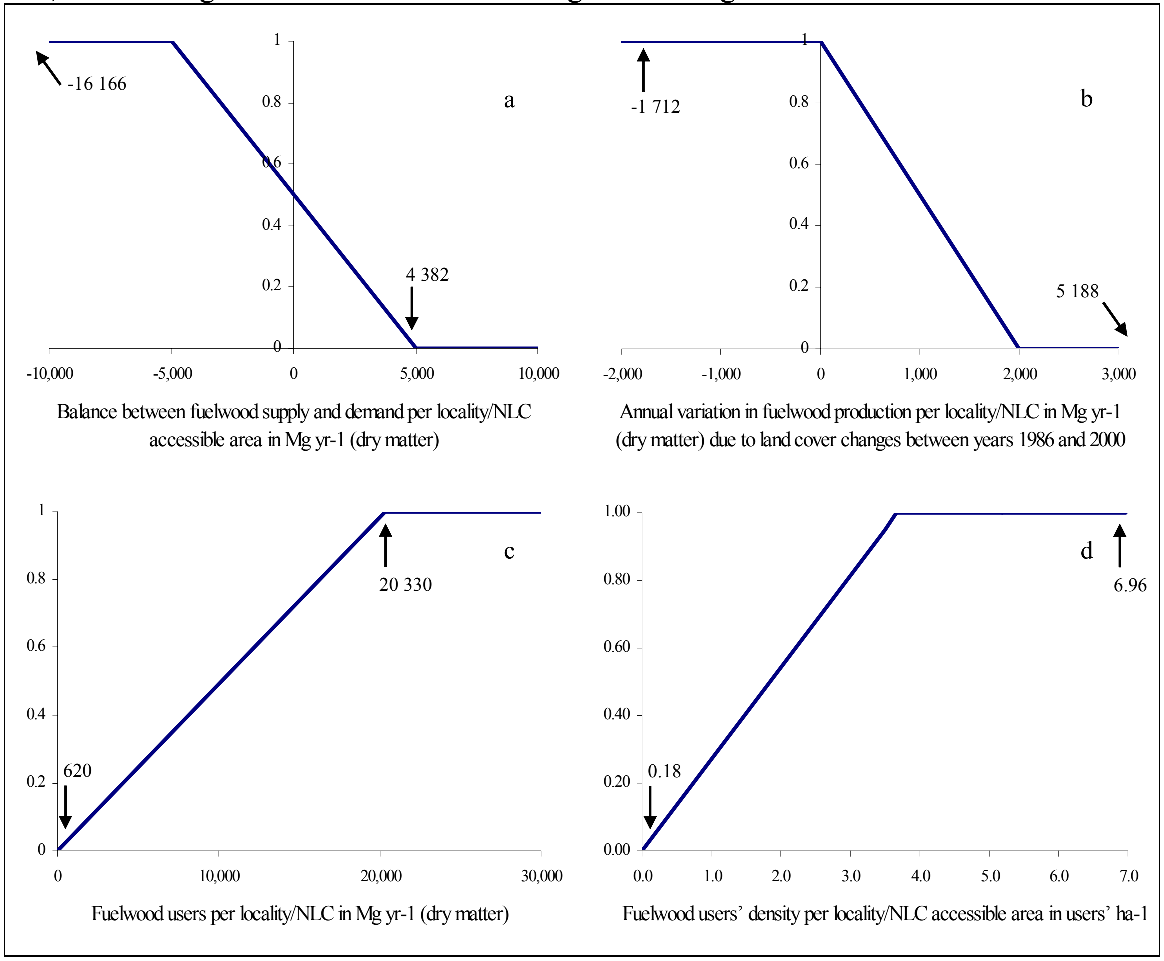
Notes: All localities (n = 298) with at least 20 households using fuelwood were analyzed in both approaches. Selected localities account for 95% of total fuelwood consumption in the *Purhepecha* Region. (†) Confidence intervals were set based on minimum and maximum input assumptions. Uncertainties in basic data were incorporated into the analysis for: 1) land cover productivity, 2) accessibility, 3) number of mixed users, and 4) per capita consumption (Ghilardi et al., 2007). (‡) 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 Appendix C 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).

Scheme 1. Simplified workflow of the WISDOM grid-based model for sub-county fuelwood supply/demand spatial patterns analysis.



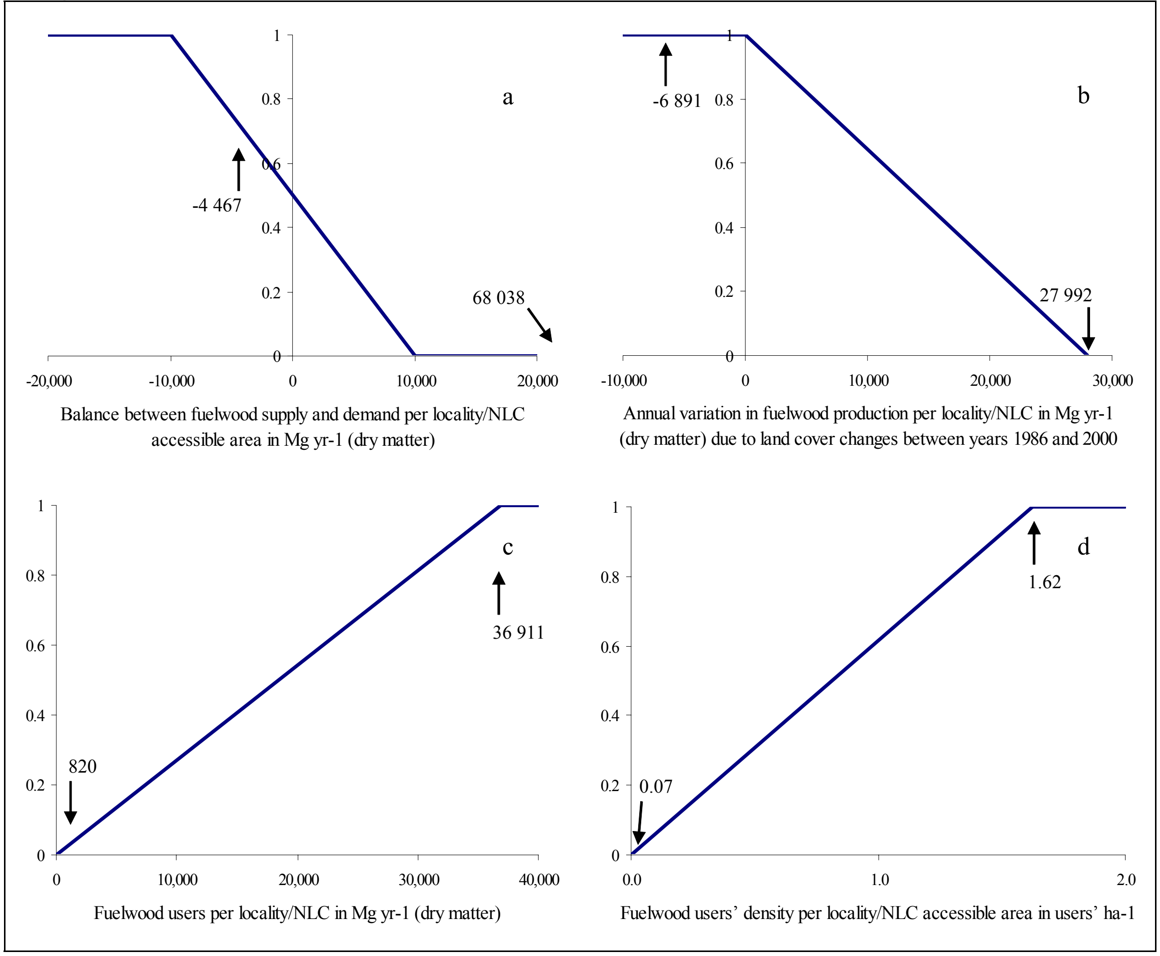
Notes: All processes (usually shown as rectangles), loops (i.e. iterative data flows by which single localities are recruited) and MCA analyses were obviated from the workflow for simplicity. NLC = Neighbor Localities Cluster: the step by which adjacent accessible areas of nearby localities are merged into one NLC was also obviated from the workflow for simplicity. BSU = Basic Spatial Unit of analysis. FPI = Fuelwood Priority Index. NRFW = Non-Renewable Fuelwood.

Graphic 1. Linear value functions for four of the six indicators used in the construction of the FPI, considering accessible areas for walking fuelwood gatherers.



Notes: Arrows show maximum and minimum real values for each indicator.

Graphic 2. Linear value functions for four of the six indicators used in the construction of the FPI, considering accessible areas for both: walking fuelwood gatherers and fuelwood gatherers using motorized vehicles.



Notes: Arrows show maximum and minimum real values for each indicator.

V. CONCLUSIONES GENERALES

A lo largo de los tres capítulos centrales de la presente tesis se describió un enfoque metodológico novedoso, denominado WISDOM por sus siglas en inglés, el cual permite analizar los sistemas de oferta y demanda de madera para energía, particularmente leña, a través de múltiples escalas y desde una perspectiva integrada y comprehensiva; la cual fomenta el diálogo entre las agencias gubernamentales forestal y energética, al mismo tiempo que facilita el diseño de políticas y estrategias coherentes para el sector.

Partiendo de una perspectiva nacional, 2,395 municipios (de un total de 2,424 en México en el año 2000) fueron categorizados según el número, densidad e incremento medio anual de los usuarios de leña; el porcentaje de casas que utilizan leña para cocinar; la resiliencia en el consumo de leña debida a factores culturales; y la magnitud y tendencia de las coberturas del suelo útiles como fuente de leña. El análisis permitió identificar 304 municipio críticos, distribuidos en 16 grupos ó clusters ó hot spots. Siguiendo un enfoque similar, pero incorporando variables espaciales emergentes, se analizó uno de los grupos de municipios prioritarios identificados en el paso anterior, conformado por 16 de los 304 municipios críticos. Dentro de éste grupo o hot spot se identificaron 20 localidades críticas, de un total de 787 en la área de estudio, las cuales resultaron agrupadas en 8 grupos distribuidos en 6 municipios adyacentes.

Las evaluaciones nacionales empleando la metodología WISDOM (orientadas a identificar grupos de municipios críticos), sirven para incorporar el uso tradicional de combustibles de madera dentro de las agendas energéticas nacionales. Por otra parte, los análisis sub-municipales (orientados a identificar localidades críticas), sirven para diseñar e implementar acciones concretas ó proyectos de intervención sobre grupos de localidades específicas.

Argumento que el enfoque propuesto es novedoso porque, partiendo de un panorama nacional, permite identificar aquellas localidades donde la situación respecto al abasto y uso de leña es más critica, resolviendo el antiguo dilema entre valores nacionales agregados vs. estudios de caso puntuales pero dispersos. El enfoque ayuda a concentrar los recursos sobre aquellas situaciones críticas particulares, utilizando información disponible, poco recursos financieros y humanos, y una metodología relativamente sencilla.

En síntesis, los beneficios principales de la metodología propuesta incluyen:

- Fomenta una visión holística del sector; mientras identifica áreas blanco prioritarias, donde las acciones deberían ser concentradas para así optimizar el uso de recursos humanos, institucionales y financieros disponibles.

- Puede utilizarse para promover el uso sustentable de la leña, y la madera para energía en general, la cual es una fuente renovable de energía, ampliamente disponible, y capaz de contribuir al desarrollo sustentable de los municipios y localidades más marginados.

- Dentro del contexto del cambio climático, los resultados de las evaluaciones nacionales aportan información robusta y espacialmente explícita a los inventarios nacionales de gases de efecto invernadero (GEI). Por su parte, las evaluaciones sub-municipales permiten cuantificar, dentro de determinados intervalos de confianza, la madera extraída de manera no-renovable, el cual es un dato clave para calcular la línea de base en proyectos de emisiones evitadas de CO_2.

El uso de madera con fines energéticos tiene un enorme potencial dentro de las opciones bioenergéticas. Tanto en México, como en el resto de los países en vías de desarrollo, se espera que los actuales patrones de uso tradicional se mixturen con patrones de uso moderno, con un consiguiente aumento de la demanda de madera para energía paralelo a la diseminación de plantaciones energéticas. Dentro de este panorama, los modelos espaciales y multi-escalares para la evaluación de este recurso van a ser cada vez más necesarios. Espero que los resultados y metodologias presentadas, así como aquellas actualmente en desarrollo por el laboratorio de bioenergía de la UNAM, sean aplicadas ampliamente en diferentes regiones y países; sirviendo como herramientas escenciales de apoyo y planeación para el proceso de transición energética global.

V.1 Direcciones futuras de investigación

Algunos temas de interés en el corto y mediano plazo son:

- Conducir análisis sub-municipales sobre otras áreas prioritarias de México, de preferencia cubriendo zonas macro-ecológicas variadas (e.g. zonas áridas, tropicales húmedas y sub-húmedas, etc.) . La limitante para éste paso es contar con mapas de cobertura del suelo re-clasificados a partir de imágenes de satélite de al menos 30mts/pixel de resolución. Al momento de terminar ésta tesis, la SEMARNAT[26] ha decidido liberar el total de imágenes SPOT de 10mts/pixel para todo el territorio Mexicano. Por su parte, entre Julio de 2008 y enero de 2009, el USGS[27] va a liberar todas las imágenes Landsat desde el comienzo del proyecto en 1982.

- Desarrollar escenarios según tendencias en los valores de oferta (e.g. patrones espaciales de cambio de uso del suelo, vulnerabilidad de los ecosistemas forestales al cambio climático, etc.) y demanda de madera para energía (e.g. tendencias en el número y distribución de usuarios de leña según INEGI 1990, 2000, 2010, cambios en los patrones de consumo de leña por variaciones significativas en el precio de los combustibles alternativos, etc.).

- Explorar los alcances de la metodología para evaluar los patrones espaciales de oferta y demanda de carbón vegetal y de uso leña por pequeñas industrias.

- Ampliar las aplicaciones del modelo como herramienta de apoyo para los inventarios nacionales de gases de efecto invernadero y para calcular líneas de base para proyectos de emisiones evitadas de CO_2 que consideran el cambio de biomasa no-renovable a renovable.

- Explorar con mayor detalle los supuestos de productividad de madera disponible para energía en general, y en específico para leña, buscando preferentemente referencias y estudios de caso conducidos en México. Así mismo, mejorar la modelación de usuarios mixtos y de ser posible, ajustar el consumo de leña per cápita según un mayor numero de estudios de caso.

- Explorar las posibilidades de dividir la estimación del balance por sectores de producción: industrial, agropecuaria, comercial y residencial. Esto permitiría ajustar algunos supuestos de productividad, accesibilidad y prácticas de extracción según características propias de cada sector, y por consiguiente dirigir mejor las recomendaciones.

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[26] Secretaría de Medio Ambiente y Recursos Naturales del Gobierno de México

[27] United States Geological Survey

- Explorar mecanismos para la actualización periódica de la bases de datos geo-referenciadas.

- Aunque los análisis nacional y sub-municipal fueron conducidos mediante sub-rutinas personalizadas (e.g. esquema 1 del capítulo IV), sería muy provechoso desarrollar un software o interfaz amigable con el usuario, a fin de facilitar la aplicación del modelo, para cada escala de análisis, sobre otros países y regiones.

- Aplicar la metodología desarrollada por Anastasiou (2006) para estimar biomasa aérea mediante la digitalización de ortofotos a escalas 1:10,000 ó 1:20,000. Dependiendo de la fecha de adquisición de la fotografía, éste tipo de análisis permitiría estimar el balance entre la oferta y la demanda para un localidad en particular con un grado considerable de precisión, sin necesidad de tomar datos de campo.

- Utilizar la metodología, en sus diferentes escalas de aplicación, como herramienta de colaboración en la evaluación de riesgos a la salud por emisiones de humo de leña al interior de los hogares rurales.

- Explorar en profundidad la dependencia escalar de las relaciones existentes entre la oferta y la demanda de leña, y de combustibles de madera en general. Existen herramientas teóricas que podrían ser de utilidad y revelar relaciones inter-escalares de interés, como por ejemplo la teoría fractal. Con respecto a éste tema, el autor de la presente tesis está escribiendo una comunicación breve titulada: *Influence of scale-dependent variables in woodfuels supplies estimations*, la cual va a ser sometida en Agosto de 2008 a la revista *Biomass and Bioenergy*.

- Explorar la correlación espacial entre la distribución de áreas cíticas por uso de leña con otras variables de interés, como por ejemplo, áreas prioritarias para la conservación, distribución de la marginación, areas de captación de agua en macro-cuencas, catastro (PROCEDE), penetración de GLP, entre otros.

- Finalmente, sería interesante trazar, al menos a grandes rasgos, algunos flujos entre los sitios de producción y los de consumo de madera con fines energéticos, en particular de carbón vegetal.

Con respecto a la validación del modelo, lamentablemente no existen metodologías de validación del modelo concluyentes para los análisis nacional y sub-municipal (capítulos III y IV respectivamente). Sin embargo, he identificado (y en algunos casos conducido) algunos procedimientos metodológicos orientados a validar y robustecer el modelo.

Considerando el análisis a escala nacional:

1) Comparar los resultados entre los análisis nacional y sub-municipal. Estos resultados se muestran en la figura 3 del capítulo IV, y dan una idea de la coherencia espacial entre los resultados a ambas escalas de análisis.

2) Determinar la correlación espacial entre los mapas de municipios prioritarios y los mapas de deforestación para México (e.g. mapa de cambio de uso del suelo a partir de las cartas de uso del suelo y vegetación a escala 1:250,000 de INEGI para el período 1993 (serie II) - 2002 (serie III)). La extracción de leña para uso residencial rara vez es causa de deforestación a nivel de todo un municipio, o un conjunto de ellos. Las causas de la deforestación en México son la

expansión de la frontera agropecuaria y la tala no regulada de los bosques nativos para la obtención de madera de aserrío. Sin embargo, el correlacionar espacialmente los municipios críticos con aquellos con mayor tasa de deforestación podría aportar información espacial relevante.

3) Determinar la correlación espacial entre los mapas de municipios prioritarios y un muestreo nacional sobre precios de la leña. El precio de la leña varía en función de una serie de variables, incluyendo la escasez de leña o la sobre-explotación del recurso. Lamentablemente no existe un muestreo sobre el precio de la leña a escala nacional.

4) Una vez procesada la información de estudios de caso presentada en el anexo IV, se podría intentar validar algunos parámetros mediante un meta-análisis.

Considerando el análisis a escala sub-municipal:

1) Validar los sitios de extracción de leña según los diferentes tipos de leñadores. Resultados recopilados en las localidades de Ajuno (NLC_Ajuno 30) (Figuras V.I - V.III), Uruapan (NLC_Uruapan 44), y Santa Fe de la Laguna (NLC_Ziróndaro 46), mediante el uso de receptores GPS, mostraron que los sitios de extracción nunca resultaron fuera de las áreas accesibles estimadas para leñadores a pie, independientemente del medio de transporte utilizado. Este dato preliminar parecería indicar una sobreestimación en las áreas de colecta de leña para uso residencial en la meseta Purhepecha. Actualmente se continúan validando los sitios de extracción como parte de un proyecto sobre emisiones evitadas de CO_2 por la implementación de estufas eficientes de leña.

2) Realizar entrevistas con los usuarios de leña, y de ser posible, con los vendedores locales a fin de conocer como perciben el grado de dificultad en el abasto de leña, y como éste ha variado en los últimos años. Dos tesis de maestría conducidas en las localidades de Ajuno (García-Burgos, 2007) y Santa Fe de la Laguna (Puentes, 2002) contiene resultados de encuestas de este tipo.

3) Evaluar el eventual efecto de los límites legales en la colecta de leña para uso residencial.

4) Evaluar el impacto de la extracción de leña sobre el bosque, con énfasis en la extracción de especies preferidas para leña. Dos tesis, una de maestría (Puentes, 2002) y otra de doctorado (Rüdger, 2006) han abordado éste tema, sin embargo, son estudios de caso puntuales poco representativos de la variación espacial. El método más robusto para validar este punto, amén de un meta-análisis basado en los estudios de caso el anexo IV, el cual puede resultar sumamente complejo, es el uso de imágenes satelitales sucesivas. Por ejemplo, el análisis conducido sobre la meseta Purhepecha corresponde al año 2000. El uso de imágenes recientes serviría para corroborar que ocurrió con las áreas forestales más susceptibles de degradación, aunque no se podría concluir si fue la extracción de leña la única causa. Una manera de dirigir la atención al efecto aislado de la extracción de leña, es considerar solamente los bosques de pino-encino que cambiaron a bosques de pino, ya que los encinos son casi exclusivamente utilizados con fines energéticos. Un análisis preliminar de este tipo mostró masas forestales que sufrieron ésta transición cerca de la localidad de Comachuén, una de las localidades críticas.

Figura V.I. Validación de sitios de extracción de leña en la localidad de Ajuno.

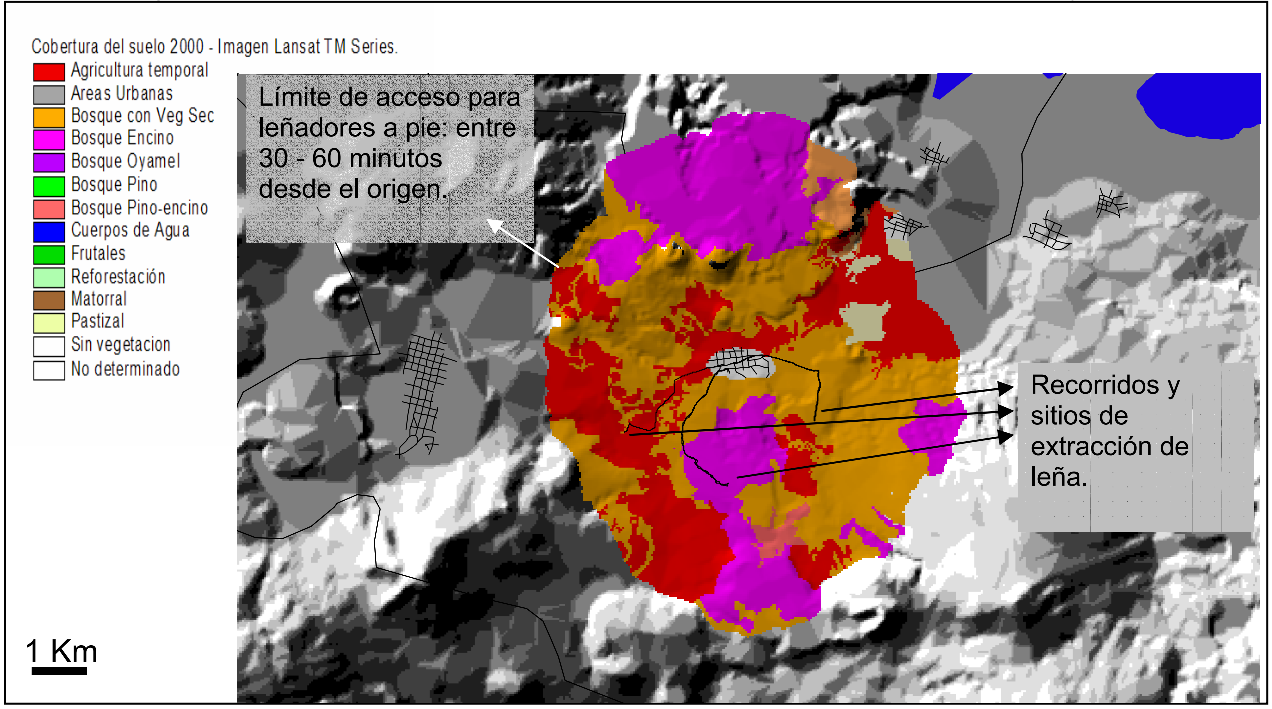


Figura V.II. Validación de sitios de extracción de leña en la localidad de Ajuno.

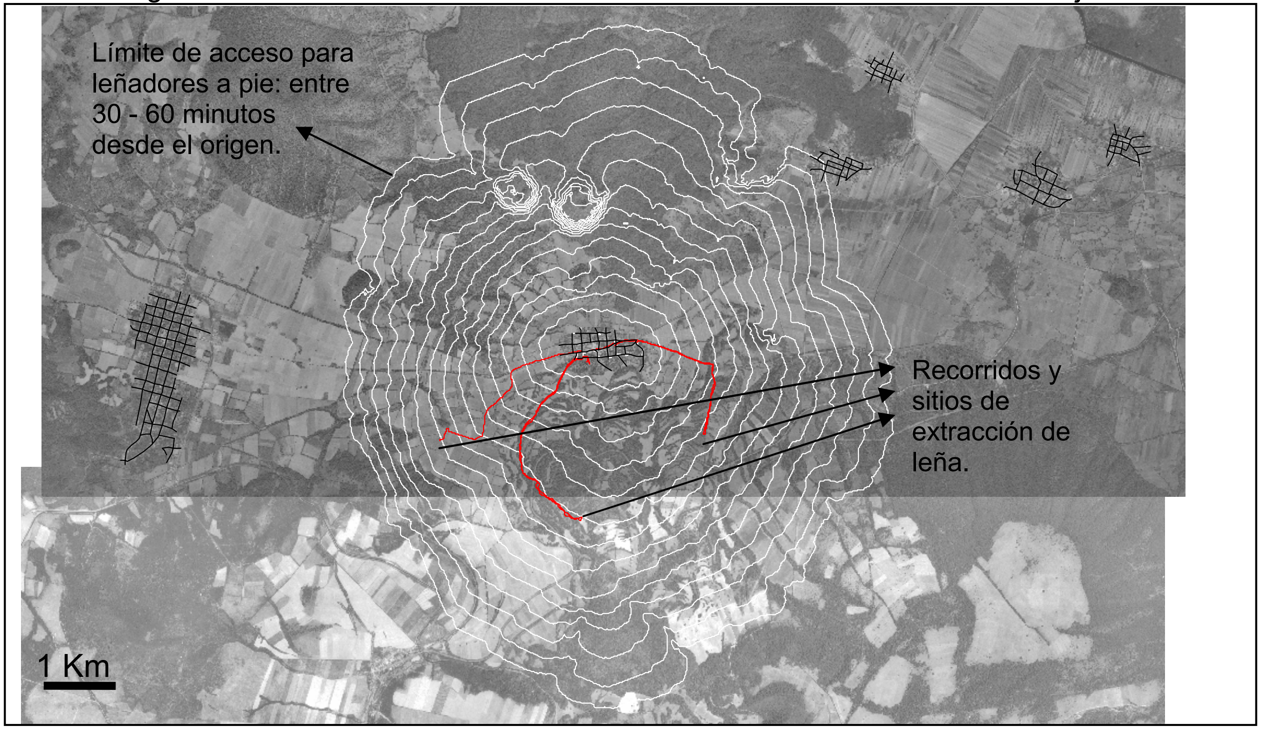
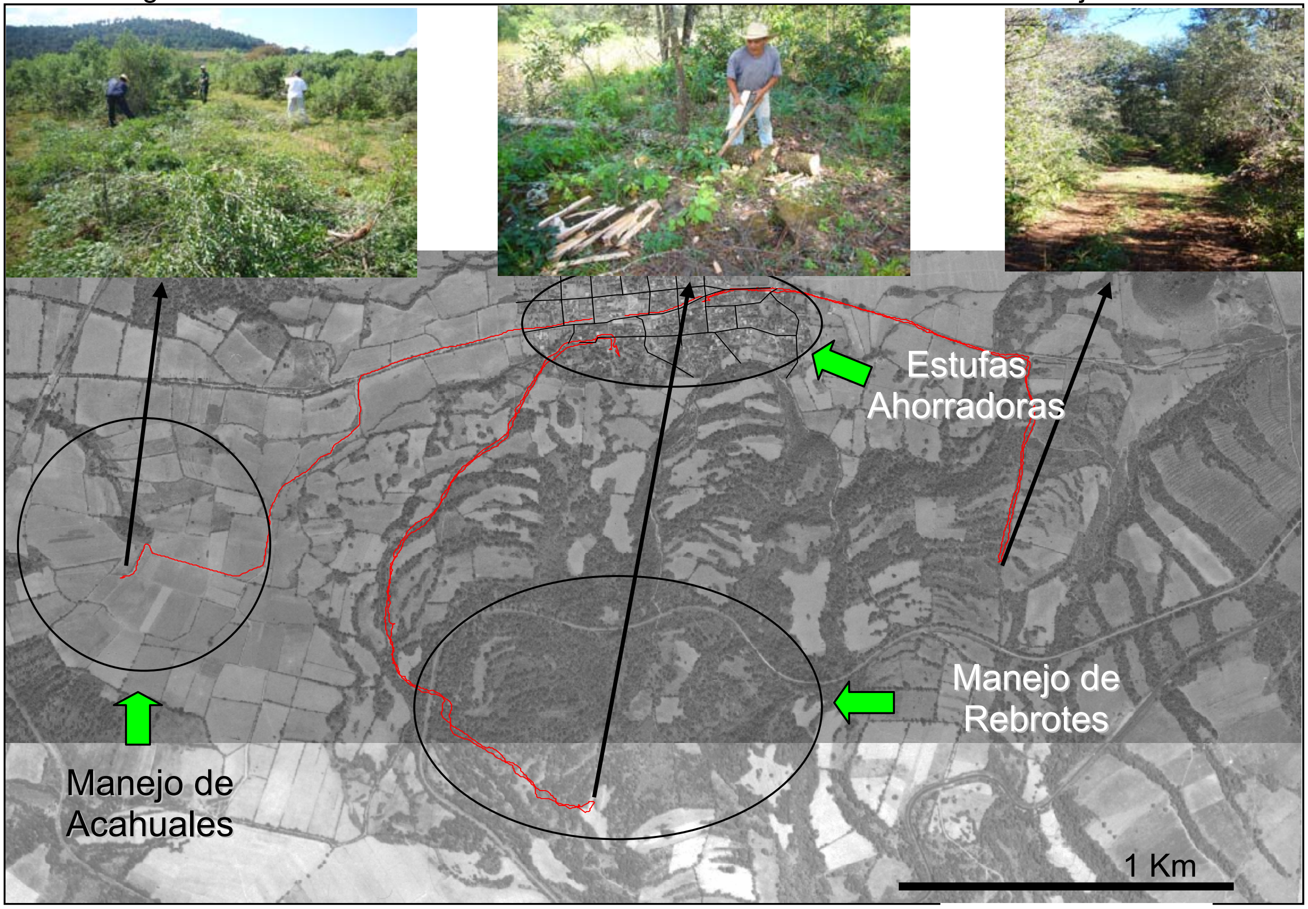


Figura V.III. Validación de sitios de extracción de leña en la localidad de Ajuno.



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ANEXO I: Metodologías para estimar la oferta de madera disponible como leña

Es necesario definir primero que tipos de biomasa tienen potencial para un uso energético o combustible. Según Ghilardi *et al.* (2006), los bio-combustibles primarios son toda aquella materia de origen orgánico (i.e. biomasa), que no es fósil, y que se destina o tiene algún potencial para la producción de energía[29]. Las principales fuentes de biomasa para energía son productos y residuos forestales, agropecuarios, agroindustriales y municipales, como por ejemplo la leña, los rastrojos, las excretas del ganado, el bagazo de la caña, o los residuos municipales sólidos. En la presente tesis se definió a la leña como toda aquella madera (i.e. biomasa leñosa) que conserva su estructura original (a diferencia del carbón vegetal, el licor negro, el metanol, los aceites pirolíticos, o los productos procedentes de la gasificación) y cuya combustión intencional puede aprovecharse como fuente de energía. Por lo tanto, las fuentes de leña son los árboles (bosques nativos, plantaciones y árboles fuera del bosque) y los residuos de la explotación forestal (aquellos que quedan en los sitios de extracción y en los aserraderos). Los residuos de la explotación forestal no fueron considerados como una fuente de oferta de leña significativa para uso del sector residencial en México. Así, la única fuente de leña para uso residencial en México es la biomasa leñosa aérea y muerta proveniente de bosques nativos y árboles fuera del bosque[30]. Es importante mencionar que la madera residual de actividades de cambio de uso del suelo (e.g. roza-tumba-quema, tala ilegal, etc.) no se considera como parte de la oferta renovable de leña. El cambio de cobertura del suelo de bosque a no bosque se incluyó dentro de la presente tesis como un indicador espacial del decremento futuro en la oferta de leña, sin considerar el aumento temporal y efímero de madera disponible para leña y carbón.

A continuación se describen brevemente los métodos más comunes empleados en ecología para estimar biomasa en estudios de vegetación, y se analiza cómo la información generada por estos métodos puede utilizarse para estimar la oferta de leña.

Independientemente de la diversidad de metodologías desarrolladas para estimar biomasa en estudios de vegetación, es importante identificar primero cuales componentes de una u otra cobertura vegetal son de nuestro interés (e.g. hojas, ramas, fuste, raíces, materia muerta, etc.). Esto va a depender básicamente de los objetivos de investigación. Así por ejemplo, la mayoría de los inventarios forestales utilizan metodologías para estimar la biomasa del fuste limpio (sin corteza) de especies comerciales con un diámetro a la altura del pecho (DAP)[31] mayor a 10 cm (e.g. IFN, 1994). Por otro lado, los trabajos que buscan evaluar el carbono almacenado en la vegetación, requieren de una cuantificación completa de la biomasa en cada componente. Dependiendo de la escala de análisis (i.e. precisión requerida), utilizan metodologías de estimación que contemplan la biomasa aérea y subterránea de cada especie vegetal presente en cada cobertura de interés, junto a la biomasa (viva y muerta) del mantillo y el suelo (e.g. Ponce-Hernández, 2004). Evidentemente, no toda la biomasa de origen vegetal tiene un potencial energético o combustible técnicamente aplicable o comercialmente favorable. En parte por sus características o estructura (e.g. raíces o biomasa del mantillo), y en parte por usos alternativos prioritarios a la generación de energía (e.g. madera para aserrío de fustes limpios). Creo pertinente enfocar esta primera parte del texto, de revisión y síntesis, hacia aquellas metodologías destinadas a la cuantificación de la biomasa leñosa aérea de árboles y arbustos para diferentes tipos de coberturas vegetales, forestales y no-forestales[32]. Posteriormente voy a

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[29] Como se mencionó en la introducción, se suele denominar habitualmente como “bio-combustibles” a sólo dos de los bio-combustibles líquidos más comunes: el bioetanol y el biodiesel.

[30] No existen aún en México plantaciones forestales energéticas.

[31] Por convención, corresponde al diámetro del árbol medido a 1.30 mts de altura.

[32] Para una definición de bosque y clasificaciones relacionadas con diferentes coberturas vegetales del suelo, favor de consultar Brown (1997) pag. 8, y FAO (2005) pags. 353-354.

resumir algunas de las metodologías para estimar biomasa muerta leñosa, y finalmente voy a explorar cómo utilizar la información generada por estas metodologías para estimar la biomasa aprovechable como combustible, particularmente como leña dentro de un patrón de uso tradicional.

A.I.1 Biomasa aérea

Se ha definido a la biomasa aérea de un árbol o arbusto como el total de materia orgánica presente por encima del nivel del suelo incluyendo hojas, ramillas, ramas, fuste y corteza (Brown, 1997). La densidad de biomasa leñosa para un tipo de cobertura vegetal corresponde al peso de la biomasa aérea presente en el conjunto de árboles y arbustos que componen dicha cobertura, expresado en toneladas de materia seca[33] por unidad de área (Brown, 1997). La biomasa aérea total para una región o un país es entonces el producto entre la superficie de cada tipo de cobertura vegetal y su respectiva densidad de biomasa[34].

A.I.1.1 Método destructivo

La metodología mas precisa para estimar biomasa aérea se denomina "de medición directa" ó "destructiva" (Brown and Lugo, 1982; Cannell, 1982; FAO, 2005; Fearnside, 1987, 1988; Olson *et al.*, 1983; Reichle, 1981)[35]. Consiste en seleccionar aletoriamente una muestra de árboles o arbustos, por cada clase diamétrica, tomar las medidas de altura del fuste (H) y DAP, Y finalmente pesar las diferentes partes mediante la tumba y el seccionado en fuste limpio, corteza, ramas, ramillas y hojas (las ramillas y hojas suelen pesarse juntas). Se utiliza para la caracterización vegetal leñosa de un área de estudio en particular, sin embargo, presenta serias limitaciones cuando se busca extrapolar los datos para cubrir regiones mucho mas extensas que el área de muestreo (e.g. Fearnside, 1987, 1988). Es decir, esta metodología es útil para estudiar una cobertura vegetal leñosa sobre un área de estudio específica, pero no es confiable para hacer inferencias sobre otras poblaciones, aunque pertenezcan a la misma categoría o tipo de cobertura (Brown *et al.*, 1989; Brown and Lugo, 1992). La limitante principal para extrapolar y escalar la información es que tanto el número de parcelas de muestreo (i.e. *plots)* como el número de árboles muestreados por parcela son siempre muy pocos para ser representativos de áreas extensas (Brown and Lugo, 1992). Otra limitante es que al ser estudios tan puntuales, no se incorpora la heterogeneidad espacial inherente a una macro-región, la cual está determinada por factores climáticos, edáficos, topográficos, de historia de uso del suelo, de edad y estructura de la cobertura, entre otros (Brown, 1996). En otras palabras, cuando consideramos un país o una macro-región, los distintos estudios de medición directa realizados sobre una cobertura vegetal específica (e.g. selva tropical lluviosa), no están distribuidos aleatoriamente. Los sitios de estudio son seleccionados según objetivos diferentes a la mera estimación de la biomasa aérea (e.g. potencial para la producción de carbón vegetal en una localidad rural, a partir de los bosques circundantes).

Una metodología alternativa para superar estas limitantes es el uso de información primaria generada por los inventarios y sub-inventarios forestales nacionales. Éstos recolectan una gran

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[33] Se considera un índice de humedad remanente a partir del secado en hornos (Brown, 1997; FAO, 2005).

[34] Los tipos o categorías de coberturas vegetales dependen directamente de la escala de análisis. En términos generales, a mayor resolución, se pueden definir más categorías, o bien diferentes criterios de clasificación. Por ejemplo, en imágenes de alta resolución se pueden llegar a incluir los árboles fuera del bosque e inclusive estimar su densidad de biomasa (Anastasiou, 2006).

[35] Tuve la oportunidad de colaborar junto a E. Riegelhaupt y T. Arias en un muestreo destructivo para estimar existencias en bosques de encinos del sur de Querétaro. El estudio forma parte de un análisis de viabilidad para el aprovechamiento de la especie para hacer carbón vegetal. Enrique Riegelhaupt es consultor especializado en forestería de la FAO y cuenta con más de 35 años de experiencia en el tema. Ha trabajado muchos años junto a Teresa Arias en el uso tradicional de la leña en México.

cantidad de datos a partir de un diseño de muestreo representativo para los tipos de coberturas arbóreas más importantes (i.e. bosques y selvas) a escalas sub-nacional o nacional (Brown, 1997; IFN, 1994; Palacio-Prieto *et al.*, 2000).

A.I.1.2 Densidad de biomasa aérea a partir de información generada por inventarios forestales

Como información de base se utiliza el volumen inventariado de fuste limpio por ha. La ecuación general para calcular la densidad de biomasa aérea δB_A en toneladas de materia seca por hectárea (tMS/ha) es la siguiente (FAO, 2005):

$$\delta B_A = V * \delta * FEB \qquad \text{(AI.1)}$$

Donde V es el volumen del fuste limpio inventariado en m3/ha; δ la densidad de la madera en toneladas de biomasa secada en el horno (tMS) / m3 "verde" o unidades equivalentes (e.g. gr/cm^3); y FEB el factor de expansión de la biomasa: coeficiente para convertir la biomasa del fuste limpio (sin corteza), en biomasa del fuste con corteza, más ramas, ramillas y hojas.
El volumen del fuste limpio V se calcula como el producto entre la altura del fuste[36] y el área basal (AB) o el diámetro a la altura del pecho (DAP=1.30 mts). Se debe estimar el grosor de la corteza.

La densidad se calcula mediante un promedio ponderado de la densidad por representatividad de cada una de las especies presentes.

$$\delta = V_{sp1}/V * \delta_{sp1} + V_{sp2}/V * \delta_{sp2} + ...+ V_{spn}/V * \delta_{spn} \qquad \text{(AI.2)}$$

Donde V_{spx} es el volumen de cada una de las especies en m^3, de la 1 a la n; V el volumen total en m^3; y δspx la densidad de cada especie en tMS/m^3, de la 1 a la n. Sin embargo, la gran mayoría de las veces no se cuenta con información sobre las densidades de cada especie. Brown (1997) recomienda estimar una densidad promedio ponderada a partir de densidades conocidas y completar los datos faltantes a partir de tablas que reportan medias aritméticas para macro-regiones ecológicas (e.g. Reyes *et al.* (1992) para selvas tropicales de África, América y Asia). El propio trabajo de Brown (1997) reporta densidades para 1180 especies tropicales.

El factor de expansión de la biomasa FEB es la relación entre la densidad de la biomasa aérea <u>total</u> en tMS/ha, para árboles de más de 10cm de DAP, Y la densidad de la biomasa aérea <u>inventariada</u> (fustes limpios) en tMS/ha. Se han calculado FEBs para bosques de latifoliadas (Brown, 1997) y coníferas (de Jong, 2001; Peters, 1977). A modo de ejemplo, presento una ecuación para estimar FEBs para bosques de latifoliadas tropicales (Brown *et al.*, 1989; Brown and Lugo, 1992).

$$FEB = e^{[3.213 -0.506 * \text{lnBA}]} \text{ para } \delta B_A < 190 \text{ tMS/ha} \qquad \text{(AI.3)}$$
$$FEB = 1.74 \text{ para } \delta B_A > 190 \text{ tMS/ha} \qquad \text{(AI.4)}$$

Donde δBA = V * δ (ecuación AI.1), en tMS/ha.

Existe un método alternativo para calcular el factor de expansión que se basa en datos de área basal de los árboles y el número de troncos por unidad de área. Este método es conocido

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[36] La altura del fuste se calcula desde la base del árbol o punto de tocón, hasta el punto de copa o donde se inserta la primera rama principal. Existen excepciones morfológicas, las cuales no voy a desarrollar porque creo que exceden los objetivos del presente texto.

como: diámetro cuadrático de rodales o QSD por sus siglas en inglés (Masera and de Jong, 2000):

$$QSD = \sqrt{\sum D^2/n} = \sqrt{(AB/n) * (4/pi)} \qquad (AI.5)$$

Donde D es el diámetro promedio de los fustes a la altura del pecho; AB el área basal promedio, y n el número de troncos en el área de estudio. La ecuación para calcular el factor de expansión como una función de QSD es la siguiente:

$$BEF = e^{[5.7671 - 1.S309 * InQSD]} \qquad \text{para } QSD < 30 \text{ cm} \qquad (AI.6)$$
$$BEF = 1.75 \qquad \text{para } QSD > 30 \text{ cm} \qquad (AI.7)$$

La principal limitación de esta metodología es que muchos inventarios forestales toman en cuenta sólo las especies con valor comercial (e.g. IFN, 1994), las cuales no son necesariamente representativas de las especies preferidas como fuente de leña[37]. Así mismo, no se tienen en cuenta árboles con un DAP menor a 10, 30 Y hasta 50 cm (Segura and Venegas, 1999); diámetros muchas veces preferidos para la obtención de leña doméstica (Masera, 1994).

A.I.1.3 Ecuaciones de regresión a partir de información de campo

Esta metodología consiste en la aplicación de ecuaciones de regresión a tablas de volúmenes o a datos obtenidos directamente en el campo cuando la información de los inventarios es insuficiente (ver limitantes de los inventarios forestales como fuentes de información primaria). Las ecuaciones de regresión han sido desarrolladas con el objetivo de poder relacionar la biomasa leñosa aérea con datos fáciles de obtener en el campo tales como la altura de los árboles (H), el diámetro a la altura del pecho (DAP), el diámetro a la altura de tocón, la altura, el ancho y la cobertura de copas (Ayala, 1998; Brown, 1997; Brown *et al.*, 1989; Easmus *et al.*, 2000; Masera and de Jong, 2000; Ponce-Hernández, 2004). Para generar este tipo de ecuaciones se utiliza información generada por el método destructivo, obtenida de la mayor cantidad de estudios de caso disponibles (Ponce-Hernández, 2004), procurando ajustar diferentes ecuaciones para diferentes condiciones ecológicas y de tipos de cobertura arbórea o arbustiva. El trabajo realizado por Brown, Gillespie y Lugo (1989) y Brown (1997) sobre la estimación de biomasa área de bosques tropicales utilizando ecuaciones de regresión es un ejemplo clave en el uso y aplicación de esta metodología. La elección de la/s ecuación/es a utilizar debe hacerse con cuidado, prestando atención a las condiciones locales de elevación, humedad y temperatura (Brown, 1997). Es recomendable, siempre que sea posible, el derribo de algunos pocos árboles para medir el ajuste de las ecuaciones seleccionadas sobre las condiciones locales del bosque (Brown, 1997).

Las ecuaciones de regresión proveen estimativos de biomasa por árbol o arbusto en tMS o kgMS según clases diamétricas. Se pueden extrapolar los datos a tMS por unidad de superficie multiplicando por el número de árboles en cada clase diamétrica sobre una superficie determinada (densidad), y sumando luego los valores de todas las clases. Esta metodología resulta útil para estimar biomasa aérea de áreas no forestales, sin embargo, los árboles fuera del bosque pueden presentar patrones de ramificación diferentes a los de un bosque, por lo tanto, las ecuaciones para bosques cerrados no son del todo recomendables para utilizarse en bosques abiertos o en árboles fuera del bosque. Se recomienda ajustar con datos locales de peso medidos directamente (Brown, 1997).

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[37] En mi proyecto de tesis para aplicar a la candidatura, presenté un anexo con una lista de especies preferidas para leña en México, basado en una amplia revisión bibliográfica. Me remito a ese texto como referencia a este párrafo.

Presento aquí, a modo de ejemplo, dos grupos de ecuaciones: uno para bosques tropicales (Brown, 1997; Brown *et al.*, 1989) y otro para bosques templados de México (Ayala, 1998).

A.I.1.4 Ecuaciones para bosques tropicales

$y = e^{[-1.996 + 2.32 * \ln DAP]}$ (Se aplica para DAP entre 5 y 40 cm) (AI.7)
$y = 10^{[-0.535 + 0.966 * \log AB]}$ (Se aplica para DAP entre 3 y 30 cm) (AI.8)
$y = 42.69 -12.800 * DAP + 1.242 * DAp2$ (Se aplica para DAP entre 5 y 148 cm) (AI.9)
$y = e^{[-2.134 +2.530 * \ln DAP]}$ (Se aplica para DAP entre 5 y 148 cm) (AI.10)
$y = 21.297 -6.953 * DAP + 0.740 * DAp2$ (Se aplica para DAP entre 4 y 112 cm) (AI.11)

Donde Y es la biomasa del árbol expresada en kg de biomasa secada en horno; DAP es el diámetro a la altura del pecho en cm; AB el área basal en cm2. La ecuación 1.6.1 se recomienda para zonas secas, con una precipitación mayor a 900mm/año (Brown *et al.*, 1989). La ecuación 1.6.2 se recomienda para zonas secas, con una precipitación menor a 900mm/año (Martínez-Yrizar *et al.*, 1992 cit. en Brown, (1997)). Las ecuaciónes 1.6.3 y 1.6.4 se recomiendan para zonas húmedas, con una precipitación entre 1,400 y 4000 mm/año (Brown *et al.*, 1989). La ecuación1.6.5 se recomienda para zonas lluviosas, con una precipitación mayor a 4000 mm/año (Brown e Iverson, 1992 cit. en Brown (1997)).

A.I.1.5 Ecuaciones para bosques templados de México (Ayala, 1998)

Pinos:
$Pf = 0.06 (DAP^2 AF)^{0.925}$ (AI.12)
$Pc = 0.044 (DAP^2 AC)^{0.911}$ (AI.13)
$Pt = 0.084 DAP^{2.475}$ (AI.14)

Encinos:
$Pf = 0.197 (DAP^2 AF)^{0.861}$ (AI.15)
$Pc = 0.128 (DAP^2 AC)^{0.855}$ (AI.16)
$Pt = 0.283 (DAP^2 A)^{0.807}$ (AI.17)

Donde Pf es la biomasa del fuste expresada en kg de biomasa secada en horno; Pc la biomasa de la copa; Pt la biomasa total; DAP es el diámetro a la altura del pecho en cm; A, AF y AC es la altura total, del fuste y de la copa en cm respectivamente.

A.I.1.6 Resumen de las tres metodologías descriptas

En la siguiente tabla comparo las metodologías recién expuestas según tres características: la escala de aplicación, la información de base necesaria para aplicar las metodologías, y la precisión relativa esperada de los resultados.

Tabla AI.1. Resumen de tres metodologías para estimar biomasa leñosa aérea.

Metodología	**Escala**	**Información de base necesaria**	**Precisión de los resultados**
Destructiva	Local	Peso medido directamente en campo	Alta
Ecuación general	Regional Nacional	Volumen inventariado del fuste limpio(inventarios forestales), δ, y FEB	Baja (depende de la información de base y del ajuste de BEF)
Ecuaciones de regresión	Local	Datos de campo (H,DAP)	Media (depende del ajuste de las ecuaciones)
	Regional Nacional	Tablas de volumen (H, DAP) (inventarios forestales)	Media (depende de la información de base y del ajuste de las ecuaciones).

A.I.2 Biomasa muerta

La biomasa muerta comprende toda aquella materia orgánica inerte que se encuentra sobre el suelo de bosques y otras coberturas vegetales (Navarrete, 2005). Aunque la importancia de la biomasa muerta en los procesos ecosistémicos ha sido ampliamente reportada (Ver Navarrete 2005 para una revisión exhaustiva de trabajos publicados), no hay muchos trabajos que describan metodologías para la cuantificación de existencias (Harmon and Sexton, 1996). Habitualmente, la biomasa muerta se clasifica en dos categorías[38]: fina (hojas, frutas, flores, ramillas, corteza, y ramas de menos de 10 cm de diámetro), y gruesa (árboles muertos, tocones muertos y ramas de más de 10 cm de diámetro) (Brown, 1974; Fosburg, 1971; Harmon and Sexton, 1996). Una segunda clasificación para la biomasa muerta gruesa se basa en el estado de descomposición de la madera (a diferencia de la fina, ésta es siempre leñosa): fresco, intermedio y podrido, o bien, fresco y podrido (Brown and Delaney, 2000; Fosburg, 1971; Harmon and Sexton, 1996).

A diferencia de la biomasa aérea, resulta sumamente difícil estimar densidad de biomasa muerta mediante métodos indirectos, lo que plantea un serio problema metodológico para abordar las escalas regional y nacional. Esto es debido a que la cantidad de biomasa muerta varía drásticamente de un lugar a otro (Brown, 1997; Harmon and Sexton, 1996). Se ha estimado que en bosques tropicales la materia muerta varia de menos del 10% de la biomasa aérea a más del 40%, (Saldarriaga *et al.*, 1986, cit. en Brown (1997); Uhl *et al.*, 1988, cit. en Brown (1997); Uhl and Kauffman, 1990, cit. en Brown (1997)1997; Delaney *et al.*, 1997, cit. en Brown (1997)). Por regla general, sin embargo, se esperan altas densidades de biomasa muerta en bosques recientemente disturbados y maduros, y bajas densidades en bosques jóvenes (i.e. la cantidad de biomasa muerta depende del estadio de sucesión del bosque) (Harmon and Sexton, 1996). En términos de entradas y salidas, la biomasa muerta en un momento dado es igual a la tasa de decaimiento menos la tasa de descomposición. Se considera que superado un límite de descomposición o putrefacción, deja de llamarse biomasa muerta para formar parte de la materia orgánica del mantillo y posteriormente del suelo. Sin embargo, las metodologías que

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[38] Harmon y colaboradores se encuentran actualmente trabajando para generar una terminología común y de amplia aceptación para la biomasa muerta y las metodologías asociadas de muestreo y estimación. Este esfuerzo es equivalente al desarrollado por M. Trossero en relación a los combustibles de madera, y biocombustibles en general, para la FAO (FAO, 2001b).

e podido revisar para cuantificar biomasa muerta no son dinámicas, es decir, son independientes de ambas tasas de cambio en el tiempo. Se busca cuantificar el volumen o el peso de la biomasa muerta en un momento dado, suponiendo que las tasas de decaimiento y descomposición están en equilibrio.

Se han descrito dos metodologías para estimar biomasa muerta gruesa[39]: 1) parcelas de muestreo y 2) transectos, cada una de estas con múltiples variables de aplicación (Brown, 1974; Harmon and Sexton, 1996; Navarrete, 2005). Cuando se busca estimar la biomasa muerta gruesa móvil, es decir, los árboles muertos y las ramas de más de 10 cm de diámetro pero no los tocones, el método mas recomendado es el de transectos (Harmon y Sexton, 1996).

A.I.2.1 Metodología para estimar biomasa muerta gruesa móvil

La ecuación general es la siguiente (Van-Wagner, 1968; Warren and Olsen, 1964):

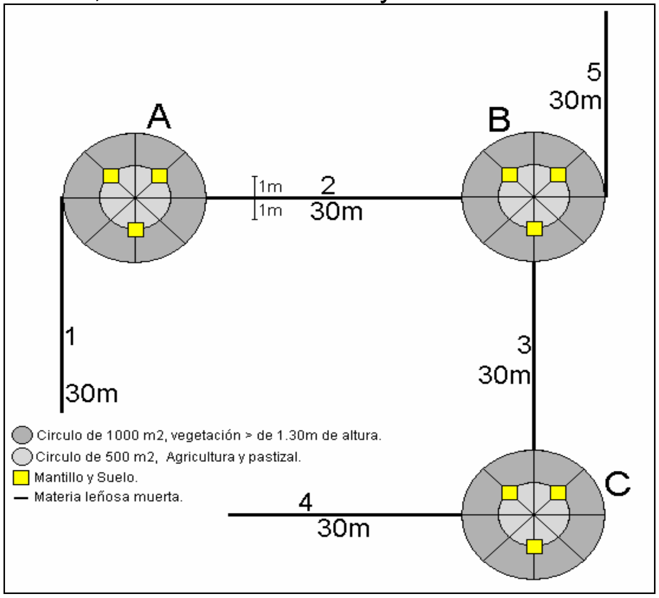
$$V= 9.869 * \sum (d2/8L) \qquad (AI.18)$$

Donde V es el volumen por unidad de área en m^3 m^{-2}, d es el diámetro de la pieza cortada por el transecto en m, y L la longitud del trayecto en m. Notar que no se requiere la longitud de las piezas, sólo el diámetro. Éste se calcula como:

$$d= \sqrt{(d_{max} * d_{min})} \qquad (AI.19)$$

Donde d_{max} y d_{min} son los diámetros máximo y mínimo respectivamente. La disposición y el número de transectos varía con el diseño experimental. La figura 1 muestra un diseño de muestreo a modo de ejemplo, el cual fue desarrollado para obtener muestras de biomasa muerta gruesa (en la figura aparece como biomasa leñosa muerta), de biomasa aérea (H y DAP), de biomasa en mantillo y de biomasa en suelo (Navarrete, 2005).

Figura AI.1 Forma y disposición de sitios de muestreo para biomasa muerta gruesa, biomasa aérea, biomasa en mantillo y biomasa en suelo.



Fuente: Navarrete, (1985).

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[39] No voy a abordar las metodologías para biomasa muerta fina porque ésta no tiene potencial combustible, al menos dentro de un patrón de uso tradicional.

Finalmente, para convertir el volumen en biomasa se multiplica por las densidades de la madera reportadas en la literatura específica, según las tres categorías de descomposición. Un ejemplo de densidades de madera muerta según 5 categorías de descomposición se encuentra en Harmon y Sexton (1996). La clasificación en categorías de descomposición se basa en las características físicas de la madera como la presencia de hojas, ramillas o corteza; la resistencia al impacto con algún objeto estándar (e.g. machete); la facilidad para ser aplastada o la desmenuzabilidad; y su color. Los indicadores biológicos como la cobertura por musgos y hongos, o la presencia de galerías de insectos no son parámetros válidos de clasificación (Harmon and Sexton, 1996).

A.I.3 Componentes leñosos de la biomasa aérea y muerta aprovechables como leña

Los componentes de la biomasa aérea y muerta aprovechables como fuente de leña doméstica o para uso a pequeña escala, son los fustes sin valor comercial explotable, las ramas con un diámetro mínimo de 10 cm[40], la corteza (dependiendo de la especie), y la biomasa muerta gruesa móvil en estado fresco o intermedio. El método destructivo es la mejor fuente de información de las existencias de fustes y ramas, pero como ya vimos, los resultados son de índole local y no es conveniente utilizarlos para estimaciones a escalas regional y nacional. La ecuación general para calcular la densidad de biomasa aérea a partir del volumen inventariado de fuste limpio por ha tiene la limitante de que los volúmenes son generalmente de especies comerciales, con DAPs mayores a 10 cm, y no existen FEBs para ramas, solo para el árbol completo a partir de la biomasa del fuste limpio. Sin embargo, esta metodología es una aproximación indirecta para estimar las existencias de biomasa aérea como fuente de leña a escalas nacional y regional. Por su parte, los trabajos que han desarrollado ecuaciones de regresión originales (i.e. utilizando el método destructivo), suelen reportar el porcentaje de biomasa en cada componente (e.g. Ross *et al.* (2001) para manglares de florida; Cannell (1985) es una revisión sobre un gran número de ecosistemas forestales; y Arias (*comm. pers.*) para los encinos del sur de Querétaro). Se puede utilizar este tipo de información, para cada tipo de cobertura vegetal de interés, para afectar los resultados de densidad de biomasa. Por ejemplo, Ross et al. (2001) reporta que el 66% de la biomasa aérea de los manglares de florida está formada por el fuste y las ramas de más de 10 cm. Por otra parte, se reporta una media de densidad de biomasa aérea total de 150 tMSjha para los manglares del golfo de México (Saenger and Snedaker, 1993). Entonces, de éstas 150 tMSjha, el 66% (99 tMS/ha) corresponde a la biomasa aprovechable como leña.

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[40] A diámetros menores, la leña no suele forma brasa (independientemente de su densidad y contenido calorífico), por ende se utiliza generalmente como combustible de ignición, y no de mantenimiento.

ANEXO II: Propiedades combustibles de la madera

El presente anexo es una breve recopilación bibliográfica sobre los principios básicos de la combustión de leña en fogones tradicionales o estufas eficientes para producir fuego y calor como fuentes de energía para cocer alimentos, calentar agua o para calefacción. Se recomienda al lector consultar la literatura especializada para profundizar en los diferentes temas tratados en el presente anexo.

A.II.1 Definición de leña a los fines de la presente tesis

Para los fines de la presente tesis he definido a la leña como toda aquella madera que conserva su estructura original y cuya combustión intencional puede aprovecharse como fuente directa de energía.

A.II.2 Composición y propiedades de la madera

A.II.2.1 Propiedades físicas de la madera

A.II.2.1.1 Forma, tamaño y aspecto

La forma de la leña influye de manera importante en la combustión, de manera general se puede decir que arde más deprisa si el diámetro no es grande, y que por lo contrario cuanto más gruesa es la leña más tardará en arder. Al tratarse la combustión de una reacción química la superficie de contacto entre el combustible (leña) y el comburente (aire) juega un papel fundamental, la forma es importante, ya que dicha superficie depende directamente de ésta.

A.II.2.1.2 Contenido de humedad

Desde el punto de vista del aprovechamiento energético de la leña, la humedad es una de las variables más importantes pues influye en el poder calorífico de la leña, determina la energía que se puede obtener por medio de la combustión. Cuando se quema la biomasa, primero se necesita evaporar el agua antes de que el calor esté disponible.

El contenido de humedad (H), o humedad relativa, representa la cantidad de agua contenida en un combustible como un porcentaje del peso, puede expresarse de dos maneras, considerando una base seca “bs” o una base húmeda “bh”. El contenido de humedad en base seca (H_{bs}) está expresado por:

$$H_{bs}=\left(\frac{P_h-P_s}{P_s}\right)*100=\left(\frac{peso\ del\ agua\ en\ el\ combustible}{peso\ \sec o\ del\ combustible}\right) \qquad \text{(AII.1)}$$

El contenido de humedad en base húmeda (H_{bh}), se da mediante la relación:

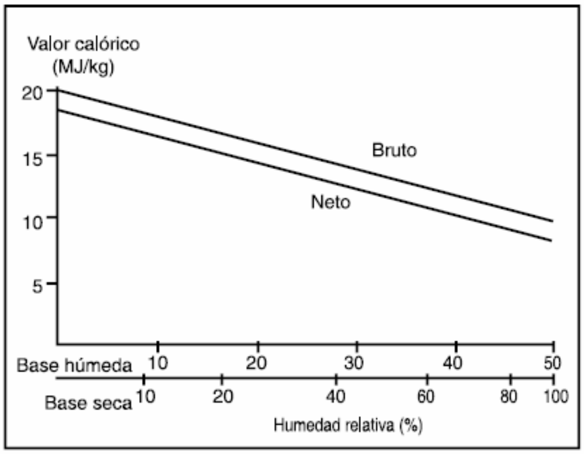
$$H_{bh}=\left(\frac{P_h-P_s}{P_h}\right)*100=\left(\frac{peso\ del\ agua\ en\ el\ combustible}{peso\ total\ del\ combustible}\right) \qquad \text{(AII.2)}$$

Donde P_h es el peso de la leña húmeda y P_s es el peso de esa misma leña después de haber sido secada en una estufa hasta haber perdido toda su humedad. De tal forma que:

$$H_{bh}=\left(\frac{H_{bs}}{1-H_{bs}}\right) \text{ y } H_{bs}=\left(\frac{H_{bh}}{1-H_{bh}}\right) \quad \text{(AII.3, AII.4)}$$

Cuanto mayor es la humedad menor es el poder calorífico, esto se debe a que cuanto más humedad contenga la leña menor materia seca por unidad de masa se tendrá disponible, y por tanto menor calor suministrado. Por otro lado, cuanto más humedad se tenga, mas cantidad de agua habrá que evaporar, lo cual consume energía, por lo que la reacción de combustión invierte parte del calor producido en evaporar esa agua. La Figura 3 muestra la variación del valor calorífico para diferentes cifras del contenido de humedad (Leach and Gowen, 1987).

Figura AII.1. Valor calorífico en función de la humedad relativa.



Notas: El Valor calórico Bruto varia con relación al Valor calórico Neto ya que no considera la energía necesaria para la evaporación del agua contenida en el combustible y ni la energía requerida para la formación de vapor de agua a partir del hidrógeno

En la práctica, para utilizarla como combustible, es necesario “secarla” a un nivel cercano al equilibrio con el ambiente, que en general se encuentra entre 7 y 15% de humedad.

A.II.2.1.3 Superficie específica

La superficie sobre la cual se lleva a cabo la reacción de la combustión está en función, además de la forma y del tamaño, de las rugosidades, nudos y otras alteraciones de la leña, cuanto mayor y más homogénea sea una superficie específica la combustión será más rápida.

La combustión se facilita si la leña esta bien seca, si hay abundante aire, si la corteza no es muy gruesa y si la superficie de contacto es suficiente. La superficie específica puede modificarse, o aumentarse, rompiendo o trozando la leña, de este modo se consigue mayor superficie de contacto y mayor superficie para la evaporación del agua, haciendo que la leña combustione mejor.

A.II.2.2 Composición química de la madera

A.II.2.2.1 Composición elemental

La composición química elemental de la leña (y la madera en general) consiste principalmente en carbono (49.5%), oxígeno (44.5%) e hidrógeno (6%), y en menor medida, nitrógeno (0.2-0.4%) y azufre (Baldwin, 1986). La fórmula empírica de la madera es $C_{11}H_{1.4}O_{0.66}$.

La composición química elemental influye en el poder calorífico, en los gases emitidos durante la combustión y en la composición química de las cenizas. De tal forma que al tener poco contenido de azufre, a diferencia de otros órganos del árbol (hojas, flores o frutos), la combustión de la madera produce poco dióxido de azufre, por lo que, desde este punto de vista, es poco contaminante; lo mismo sucede con el nitrógeno al producir pocos óxidos de nitrógeno.

A.II.2.2.2 Composición por compuestos

Los compuestos elementales recién descriptos se presentan en la madera como polímeros complejos (RWEDP, 1993a):

Celulosa	$(C_6H_{10}O_5)_x$	40-50%
Hemicelulosa	$(C_5H_8O_4)_y$	15-25%
Lignina	$(C_9H_{10}O_3(CH_3O)_{0.9\text{-}1.7})_z$	20-30%

Las proporciones de cada polímero varían considerablemente dependiendo de la especie de leña.

La celulosa es un polímero lineal con una masa molecular superior a 100,000. Por su parte, la hemicelulosa no es un compuesto concreto, sino que bajo este término se engloba un conjunto de compuestos polimerizados de masa molecular inferior a 30,000. La lignina es el agente de unión de las fibras de celulosa (Camps and Marcos, 2002).

La composición química por compuestos, influye en los gases emitidos en la combustión y en la composición de las cenizas.

A.II.2.2.3 Poder calorífico

El poder calorífico se refiere a la cantidad de energía que desprende la unidad de masa de un combustible cuando éste se quema. Se mide en unidades de energía por unidad de masa (cal/g, J/g, etc.).

El poder calorífico de la leña depende del contenido de humedad y de sus tres principales constituyentes, La lignina tiene el valor más alto (26.63 MJ/kg), mientras que la celulosa y la hemicelulosa tienen un valor de 17.46 MJ/kg, por lo que este valor varía de una especie a otra dependiendo del porcentaje de cada componente. La proporción de oxígeno e hidrógeno en la celulosa es similar a la de una molécula de agua, por lo que no existe contribución del hidrogeno para un mayor poder calorífico ya que éste depende del carbón y de otros compuestos resinosos de alto poder calorífico (RWEDP, 1993a).

Para madera completamente seca, la cantidad de energía por unidad de peso es más o menos igual para todas las especies, con un promedio de valor calorífico bruto de 20 MJ/kg para madera de tronco. Los valores pueden variar ligeramente de este promedio, según el contenido de ceniza: para ramas pequeñas, tienden a ser más bajos y más variables. Sin embargo, en la práctica, la humedad relativa es el factor más importante que determina el poder calorífico.

Comúnmente se utilizan dos tipos(Camps and Marcos, 2002):

Poder Calorífico Superior (PC_S): También es llamado calor de combustión superior e indica la relación entre la energía total liberada por la combustión y el peso del combustible, en este caso el agua de combustión es recogida en forma líquida.

Poder Calorífico Inferior (PC_I): Representa la cantidad efectiva de energía generada por la combustión, después de considerar energía utilizada para la evaporación de agua libre y combinada. Indica el calor desprendido por un kg de combustible, en una combustión en la que el agua del combustible se libera en forma de vapor

El PC_I es menor que el PC_S porque no incluye i) la energía necesaria para la evaporación del agua contenida en el combustible y ii) la energía requerida para la formación de vapor de agua a partir del hidrógeno; por lo tanto, la diferencia entre el PC_S y el PC_I depende principalmente del contenido de humedad y de hidrógeno en el combustible. El poder calorífico de la madera, expresado en base seca, varía en una proporción muy pequeña, dependiendo, como ya se comentó, del contenido de humedad; el poder calorífico superior o bruto y el poder calorífico inferior o neto se expresan mediante las siguientes relaciones:

$PC_I = (1-1.12H_{bh})*Ho$ y $PC_S = (1-H_{bh})*Ho$ (AII.5, AII.6)

Donde, Ho = Entalpía de la madera en base seca; PC_S = Poder calorífico superior; PC_I = Poder calorífico inferior; y H_{bh} = Contenido de humedad de la madera en base húmeda

La dependencia encargada de la elaboración del Balance Nacional de Energía (SEMIP y SENER actualmente) utiliza el poder calorífico superior (PC_S) de los combustibles. Estas dependencias han utilizado diferentes PC_S de la leña, a partir de 1965 y hasta 1993 se le asignó un valor de 4,400 kcal/kg (18.42 MJ/kg); posteriormente se usó un PC_S de 3,460 kcal/kg (14.48 MJ/kg). Finalmente, en 1997 la Secretaría de Energía de México (SENER) efectúo una corrección a toda la serie (1965-1997) en la que empleó un PC_S igual a 14.44 MJ/kg.

El poder calorífico de la madera secada en horno difiere poco para distintas especies de árboles. Normalmente se asume una entalpía para la madera secada en horno, igual a Ho = 20 MJ/kg (Almeida, 1990; Masera, 1993) y se utiliza el PC_S de la madera por ser el valor que se utiliza en el BNE para poder comparar los resultados. Considerando la humedad promedio nacional igual a 22% en base húmeda, al aplicar la ecuación para PC_s, se obtiene un PC_s promedio nacional igual a 16 MJ/kg de leña (Díaz, 2000).

A.II.2.3 Características físico-químicas

A.II.2.3.1 Variables de combustibilidad

Las variables de combustibilidad más importantes son el coeficiente de conductividad térmica y las que se refieren a las temperaturas y tiempos de inicio de combustión, de inflamación, temperatura de llama, etc. (Camps and Marcos, 2002).

Se denomina coeficiente de conductividad térmica a una variable termodinámica que mide la rapidez de transmisión de calor por conducción. Por su parte, el tiempo de combustión es el tiempo que tarda en comenzar la combustión de un combustible mientras que la temperatura de combustión es aquella a la que un combustible comienza su combustión, ambas variables dependen de la naturaleza del combustible (composición química, superficie específica, coeficiente de conductividad térmica, etc.).

El tiempo de inflamación se refiere al tiempo que tarda un combustible en emitir una llama, lo cual sucede a la temperatura de inflamación. El comienzo de la combustión y el tiempo en alcanzar la temperatura máxima de llama están influenciados por el contenido de humedad de la leña, una vez que se ha evaporado el agua contenida es cuando comienzan a escapar vapores combustibles que finalmente forman la llama. En la Tabla 1 se presenta un esquema simplificado del modelo de combustión de la leña, en función de la temperatura de carbonización de la misma (Camps and Marcos, 2002).

Tabla AII.1. Modelo simplificado de la combustión de la leña.

Temperatura (ºC)	0-100	100-(190-210)	(190-210)-280	280-500	>500
Producto	Materia sólida no carbonosa	Materia sólida Vapor de agua	Materia sólida Gases inflamables mezclados con vapor de agua	Materia sólida y carbonosa Gases inflamables	Carbón
Tipo energético de reacción	Endotérmica	Endotérmica	Endotérmica	Exotérmica	Exotérmica

Fuente: Berrueta (2007) .

En general las maderas más densas tienen un coeficiente de conductividad térmica más elevado, sin embargo al quemarse se produce un residuo sólido carbonoso cuyo coeficiente de conductividad térmica es muy pequeño, cuando este residuo aumenta de espesor los tiempos de combustión se hacen mas largos y la leña arderá mas despacio manteniendo por más tiempo la combustión. Por esta razón, en muchas de las ocasiones, se prefiere la leña de roble, encino y eucalipto entre otras, frente a la de pino, ya que esta última es menos densa.

La velocidad de combustión también se ve influenciada por materiales inflamables contenidos en el interior de la leña, tal es el caso de la resina. Este material arde más rápido que la pared celular de la leña, razón por la cual, para otros usos se prefiere leña más resinosa (alfarería, panadería, etc.).

A.II.2.3.2 Potencia calorífica

La potencia calorífica se refiere a la cantidad de calor desprendida por un combustible por unidad de masa y unidad de tiempo (kJ/kg.s, kW.s, kcal/kg.s,). Al iniciar la combustión se prefiere que la potencia calorífica sea grande para lograr encender la lumbre con rapidez, una vez que esto sucede se desea que se mantenga constante.

La potencia calorífica esta en función de: a) el poder calorífico del combustible; b) la forma del combustible (superficie específica); c) la colocación del combustible respecto al comburente (aire), lo cual está en relación con la entrada de aire primario y secundario; d) el coeficiente de conductividad térmica; y e) de la tecnología de combustión, es decir el diseño de la cámara donde se realiza la combustión de la leña, y del tiro de la chimenea.

A.II.3 Principios básicos de la combustión de la leña

La combustión es una reacción química en la que un elemento combustible se combina con otro comburente, desprendiendo calor y produciendo un óxido; la combustión es una reacción exotérmica. Son necesarios cuatro elementos para que inicie y tenga continuidad un fuego: 1) combustible (e.g. leña); 2) Comburente: se define como comburente a toda mezcla de gases en la cual el oxígeno está en proporción suficiente para que se produzca la combustión. Cuando el combustible es la leña utilizada en forma tradicional, el comburente es el aire, el cual contiene aproximadamente un 21% de oxígeno; 3) energía de activación (calor): para iniciar la combustión de cualquier combustible, es necesario alcanzar una temperatura mínima, llamada temperatura de ignición o punto de ignición; y 4) reacción en cadena.

La combustión es un proceso complejo en el cual los procesos de volatilización, descomposición y de combustión ocurren casi simultáneamente. La cantidad de energía liberada durante la reacción de combustión depende de la temperatura, de la presión, de los productos de la reacción y del estado del agua producido. Estos dos últimos factores son importantes porque la combustión incompleta dará lugar a la producción del monóxido de carbono y de otros materiales combustibles, que dan lugar a la pérdida de energía potencial del combustible. El estado del líquido o del vapor del agua, producido durante la combustión del hidrógeno en el combustible, tendrá efectos sobre el calor neto liberado.

Los productos la combustión de la pirolisis de la biomasa, en particular, carbón y volátiles, ocurre en dos maneras, la combustión de los volátiles y la combustión del carbón.

La composición de los volátiles es variable y depende de la temperatura de la pirólisis y del tiempo que estos volátiles se sujetan a una temperatura elevada. Así, la combustión de volátiles es un proceso complejo. Cuanto más alta es la temperatura de la zona pirolítica, tanto más severo es la descomposición de las moléculas más grandes que en las más pequeñas, que alternadamente se queman más fácilmente. El fuego de la leña produce generalmente una llama difusa. Esto consiste en un jet del gas inflamable con una reacción de la combustión que ocurre en el interfaz del aire-gas, dando por resultado la formación de los productos gaseosos calientes de la combustión y calentando el resto del gas. Los productos de la combustión son luminosos debido a su alta temperatura dando por resultado una vertical que se eleva. Durante la subida, estos productos también arrastran un poco de aire circundante.

Otro proceso, que ocurre simultáneamente, es la difusión del aire a causa de la diferencia en la presión parcial de los componentes. Esta difusión del aire en el material volátil sin quemar modifica la temperatura en la combustión del material volátil. Si la temperatura de la zona de la combustión no es suficientemente alta se forma el hollín y quedan compuestos químicos sin quemar. La temperatura puede bajar debajo de la temperatura de ignición debido al efecto del aire arrastrado o al contacto de la llama con una superficie fría.

Cuando la combustión ocurre en la superficie, el dióxido de carbono se forma con la liberación del calor. Sin embargo, si la reacción de la combustión ocurre en la cama del combustible o en el carbón a temperatura alta, entonces el dióxido del carbono se reduce a monóxido de carbono. Para evitar esto, se debe quemar con aire secundario para lograr producir únicamente dióxido de carbono y calor. Si no, dará lugar a la pérdida de calor potencial así como a emisiones contaminantes.

Durante la combustión a temperaturas de 250ºC o superiores, el 80% de la masa de la leña se evapora en una mezcla de gases flamables, conocidos como volátiles, la liberación de este proceso se denomina pirólisis. Los residuos remanentes quedan en forma de carbón o de cenizas.

Cuando la temperatura es suficientemente alta y se cuenta con la cantidad necesaria de oxígeno los subproductos que se obtienen son agua y dióxido de carbono, pero si alguna de esas dos condiciones no se cumple la combustión es incompleta se sabe que, además de CO2, se emiten partículas, hidrocarburos aromáticos policíclicos, óxido nitroso, óxido de azufre y monóxido de carbono (CO), todos con efectos adversos a la salud.

En resumen se podría simplificar el proceso de la siguiente manera:

Si un pedazo de leña se calienta hasta cerca de los 100°C, el agua que contiene hierve y se evapora o se va a las partes más frías del leño y escurre por la punta que está más lejos del fuego.

Cerca de los 200°C comienza la descomposición de la hemicelulosa, seguida por la celulosa.

A los 300°C la descomposición se hace extensiva. Alrededor del 8-15% de los compuestos permanecen como carbón fijo, el resto es liberado como gases volátiles. Además, 50% de la lignina permanece como carbón. Los volátiles producidos por esta descomposición escapan como humo o se recondensan.

Cuando los gases se escapan se mezclan con oxígeno y se queman alrededor de los 550°C y producen una llama amarilla. El 14% de la energía total de la combustión es producto del calor radiante de la llama.

La temperatura de los gases sobre la leña es típicamente de 1,100°C y está limitada por la pérdida de calor radiante y por la mezcla con aire frío del ambiente. Cuando los volátiles suben reaccionan formando hollín y humo y simultáneamente se queman al mezclarse con el oxígeno. La leña se quema en capas y cuando todo el carbón se ha quemado se producen las cenizas.

ANEXO III: Sistemas de Coordenadas utilizados

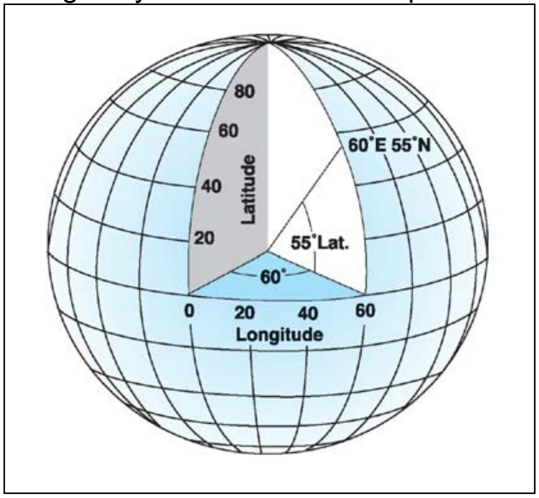
A.III.1 Sistemas de Coordenadas Geográficos

Un sistema de coordenadas es un conjunto de valores que permiten definir, a partir de un punto denominado origen, la posición de cualquier punto en el espacio y establecer su relación con otros puntos. Para definir un sistema coordenado será indispensable establecer el sistema de referencia, el cual es el conjunto de ejes, puntos o planos que convergen en el origen y a partir de los cuales se calculan las coordenadas.

Un sistema de coordenadas geográfico (SCG) utiliza una superficie esférica tridimensional para definir puntos sobre la tierra. Un SCG incluye una unidad de medida angular, un meridiano de origen y un *datum* (basado en un esferoide). La ubicación de un punto sobre la superficie terrestre se describe mediante un valor de *longitud* y de *latitud*. Ambos son valores angulares medidos desde el centro de la tierra hacia un punto en la superficie terrestre. Usualmente se utiliza el *grado* como unidad de medida angular (Figura III.1).

Si se considera a la tierra como una esfera, las líneas horizontales o *paralelos* son líneas de igual latitud, mientras que las líneas verticales o *meridianos* son líneas de igual longitud. Dos círculos máximos dividen la tierra en partes iguales: el primero denominado ecuador, que corre de este a oeste y es equidistante a los polos, y el segundo que va del polo norte al polo sur, llamado meridiano de origen (usualmente el meridiano de *Greenwich*). De esta forma la ubicación de un punto se obtiene definiendo su distancia al norte o sur del ecuador (0º), y al este u oeste del meridiano de origen (0º).

Figura AIII.1. Valores de longitud y latitud sobre una representación esférica del mundo.



Fuente: (Kennedy and Kopp, 2000).

Aunque los valores de longitud y latitud pueden localizar posiciones sobre la superficie de la tierra con exactitud, no son unidades uniformes de medida. Sólo sobre el ecuador, la distancia representada por un grado de longitud es prácticamente igual a la distancia representada por un grado de latitud. Esto se debe a que el ecuador es el único paralelo con el mismo perímetro que los meridianos (el ecuador y todos los meridianos se denominan *grandes círculos*). Hacia el norte y sur del ecuador, los paralelos se hacen gradualmente más pequeños hasta transformarse en un punto sobre los polos norte y sur, donde convergen los meridianos. A medida que los meridianos convergen en los polos, la distancia representada por un grado de longitud decrece hasta cero. Por ejemplo, en el esferoide de Clarke 1866, un grado en el ecuador equivale a 111.321 km, mientras que a 60º de latitud equivale a 55.802 km. Desde que los grados de latitud y los de longitud NO tienen una medida estándar o uniforme, NO es posible medir o representar distancias o áreas de manera precisa sobre un plano o un monitor de computadora.

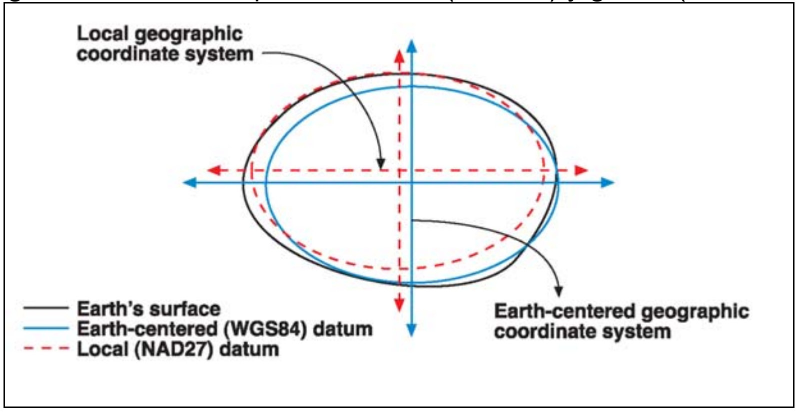
La forma y el tamaño de la tierra en un sistema de coordenadas geográfico se define según una esfera (la cual se construye a partir de un círculo) o un esferoide (el cual se construye a partir de una elipse). Asumir a la tierra como una esfera es sensato para mapas a pequeña escala (menores que 1:5,000,000). Sin embargo, para escalas mayores (1:1,000,000 o mayores) se debe representar a la tierra como un esferoide. Entre ambas escalas, la elección depende de la información a representar y la precisión de los datos de entrada.

Varios esferoides se utilizan para representar a la tierra. Generalmente, se escoge un esferoide específico para cada región o país en particular. Para América del Norte por ejemplo, se suele representar a la tierra según el esferoide determinado por Clarke en 1866, cuyos valor de semi-eje mayor (distancia entre el centro de la tierra y cualquier punto del ecuador) es de 6,378,206.4 metros, y el semi-eje menor (distancia entre el centro de la tierra y el polo norte o sur) es de 6,356,583.8 metros.

Tecnología satelital moderna ha permitido corroborar que la tierra no es un elipsoide perfecto, sino un cuerpo irregular con variadas desviaciones elípticas (el polo sur está mas cerca del ecuador que el polo norte por ejemplo). El esferoide actual más preciso para América del Norte es el Sistema de Referencia Geodésico (Geodetic Reference System -GRS 1980-) cuyos semi-eje mayor y menor son igual a 6,378,137.0 y 6,356,752.31414 metros respectivamente.

Mientras que los esferoides se aproximan a la forma de la tierra, el *datum* define la posición del esferoide relativo al centro de la tierra. El *datum* provee un marco de referencia para localizar puntos sobre la superficie terrestre. El *datum* define el origen y la orientación de las líneas de longitud y latitud. Los *datum* locales (e.g. North American Datum 1927 -NAD 27-) alinean el esferoide para que coincida con la superficie de la tierra en algún punto particular, y a partir de ese punto se calculan los otros puntos hasta cubrir una zona considerable del globo terrestre. Por ejemplo, el *datum* NAD 27 tienen su punto de origen en un rancho en Kansas, pero se ajusta a toda América del Norte considerablemente bien. Los *datum* geocéntricos, como por ejemplo el Sistema Geodésico Global (World Geodetic System -WGS 84-), no se alinean con punto alguno de la superficie terrestre, sino con el centro de la tierra, y sirven como marco de referencia global. Los *datum* geocéntricos son utilizados por los sistemas de posicionamiento global GPS (Figura III.2).

Figura AIII.2. *Datum* para uso local (NAD27) y global (WSG 84).



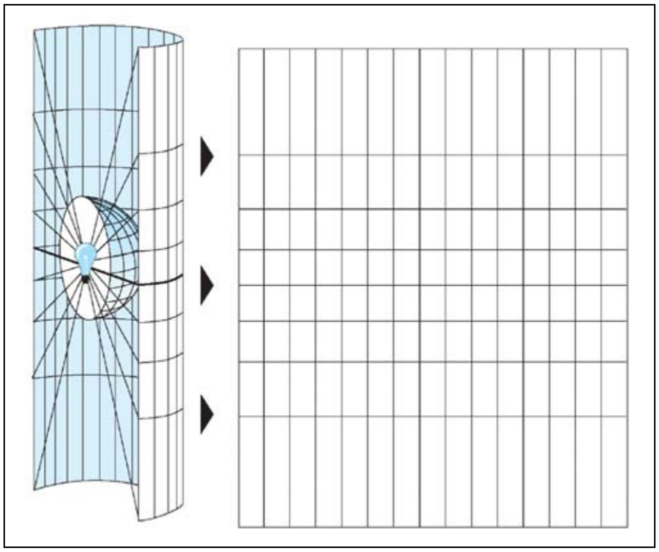
Fuente: (Kennedy and Kopp, 2000).

A.III.2 Sistemas de Coordenadas Proyectados o Proyecciones Cartográficas

Un sistema de coordenadas proyectado o proyección cartográfica se define sobre una superficie plana bidimensional. A diferencia de un sistema de coordenadas geográfico, tiene sus distancias, ángulos y áreas constantes a lo largo y ancho de sus dos dimensiones. Un sistema de coordenadas proyectado se calcula siempre a partir de un sistema de coordenadas geográfico basado en una esfera o esferoide. En un sistema de coordenadas proyectado los puntos se ubican bajo el sistemas de coordenadas **x,y**.

La transformación matemática por la cual un sistema de coordenadas geográfico tridimensional se convierte en una mapa bidimensional se denomina *proyección*. Una manera sencilla de entender una proyección es visualizar a la tierra como una esfera transparente con los meridianos y paralelos formando una estructura de alambre. Si se coloca una fuente de luz en el centro de la tierra, la malla de alambre producirá sombras sobre cualquier superficie que se le acerque. Si se envuelve a la tierra con una hoja de papel formando un cilindro o un cono, las sombras producidas por la malla de alambres (meridianos y paralelos) se proyectarán sobre el papel. La proyección consiste en fijar éstas sombras como si fuera papel fotográfico, para luego descubrir la tierra y extender la hoja de papel sobre una superficie plana bidimensional (Figura AIII.3). Cualquier tipo de proyección distorsiona las formas, áreas, distancias ó dirección vectorial de la información contenida en la superficie tridimensional. Diferentes proyecciones causan diferentes tipos de distorsión. Algunas minimizan una o dos características en detrimento de las otras; por ejemplo, puede minimizar la distorsión asociada al área en detrimento de la forma.

Figura AIII.3. Los meridianos y paralelos de un sistema de coordenadas geográfico se proyectan sobre un superficie cilíndrica como si fuesen sombras originadas por una luz en el centro de la tierra.



Fuente: (Kennedy and Kopp, 2000).

A.III.3 Proyección cartográfica utilizada a nivel nacional

La descripción de las diferentes proyecciones y sus metodologías de cálculo excede por demás el límite del presente anexo. Basta con mencionar que en México se ha utilizado con regularidad la proyección Cónica[41] Conforme a Lambert, la cual es una de las mejores para representar países completos en latitudes medias, con un rango norte-sur no mayor a 30 o 35 grados. El rango de latitud en México es de aproximadamente 18 grados (el punto más al norte en México es 32° 43´ 06´´ latitud norte, en el Monumento 206, en la frontera con los Estados Unidos de América; y el más al sur es 14° 32´ 27´´ latitud norte, en la desembocadura del río Suchiate, frontera con Guatemala).

Sin embargo, la proyección Cónica Conforme a Lambert representa las *formas* de manera más precisa que las *áreas*. Durante los análisis conducidos en la presente Tesis a nivel nacional, el cálculo de áreas es un procedimiento habitual, como se evidencia en el conjunto de ecuaciones del capítulo III. Por lo tanto, se escogió la proyección Cónica de Área-Equivalente de Albers, la cual es homóloga a la de Lambert pero preserva el área (i.e. coeficiente de deformación superficial nulo) distorsionando la forma, los ángulos y la escala. Los meridianos y paralelos pueden no intersectar en ángulos rectos. Vale mencionar que distinguir una proyección de área equivalente de una conforme no es nada sencillo a simple vista, al menos que se tomen ciertas medidas sobre el mapa.

Para comprender cabalmente como diferentes proyecciones cartográficas minimizan la distorsión de las diferentes características (forma, ángulos, áreas y escala) se sugiere consultar la literatura especializada. Un primer documento, de fácil comprensión para el público general es el de Kennedy and Kopp (2000).

Los datos de proyección utilizados en la representación del territorio nacional Mexicano (capítulos II y III de la presente Tesis) son los siguientes:

Projected Coordinate System
Projection: Albers Equal Area Conic
Central Meridian: -102.0
Standard Parallel 1: 17.5
Standard Parallel 2: 29.5
False Easting: 2,000,000.0
False Northing: 0.0
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System
Angular Unit: Degree
(0.017453292519943299)
Prime Meridian: Greenwich (0.0)
Datum: North American Datum 1927
Spheroid: Clarke 1866

A.III.4 Proyección cartográfica utilizada a nivel sub-nacional

Se escogió la proyección Universal Transversa de Mercator (UTM). La proyección UTM fue desarrollada por Lambert en 1772, y modificada por Gauss en 1822 y Kruger 1912 quienes la definieron como se conoce en la actualidad. En ella se hace una proyección de la Tierra sobre un cilindro tangente a los meridianos. Es ampliamente utilizada en México para la elaboración de cartas a escalas 1:250,000, 1:50,000 y mayores.

El globo terrestre se divide en 60 zonas norte y sur, cada una de 6 grados de longitud. Cada zona tiene su propio meridiano central. Los límites de cada zona norte son los 84 grados de latitud norte y el ecuador, los límites de cada zona sur son el ecuador y los 80 grados de latitud sur. Para las regiones polares se utiliza el sistema de coordenadas Universal Polar Estereográfico. El origen de cada zona es su meridiano central y el ecuador. Para eliminar coordenadas negativas, el sistema UTM altera los valores en su origen, así el valor dado al

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[41] Se denominan proyecciones cónica, cilíndrica o plana, en función de cómo se dobla la superficie de proyección (i.e. la “hoja de papel” de la sección A.III.2) sobre la esfera terrestre.

meridiano central en el falso este (500,000 metros), mientras que el valor asignado al ecuador es el falso norte (0 metros para zonas norte y 10,000,000 metros para zonas sur).

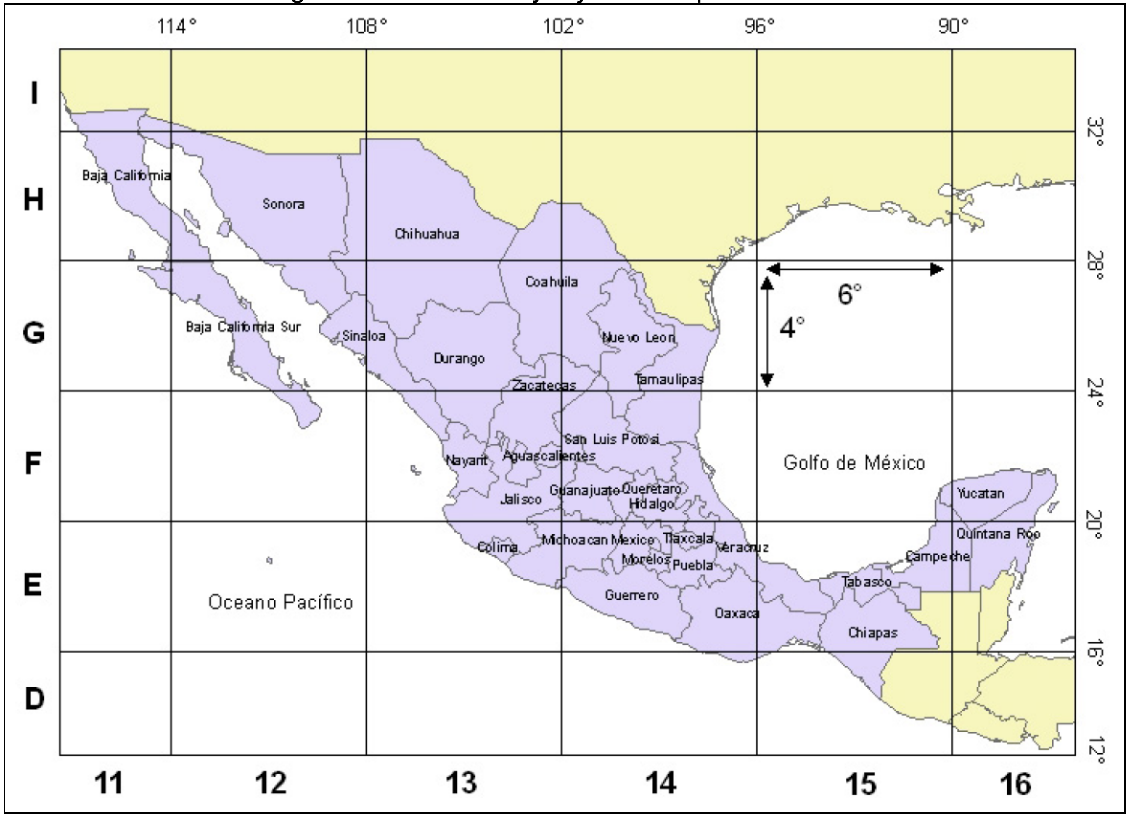
Los datos de proyección utilizados en la representación de áreas de análisis a nivel sub-nacional (capítulo IV de la presente Tesis) son los siguientes:

Projected Coordinate System
Projection: Transverse_Mercator (13N)
False_Easting: 500,000.0
False_Northing: 0.0
Central_Meridian: -105.0
Scale_Factor: 0.99960
Latitude_Of_Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System
Angular Unit: Degree (0.017453292519943299)
Prime Meridian: Greenwich (0.0)
Datum: North American Datum 1927
Spheroid: Clarke 1866

En la figura AIII.4 se puede ver que a México le corresponden las zonas 10 a 16. Cuando el área de trabajo a nivel sub-nacional comprendió áreas divididas entre 2 zonas UTM, se optó simplemente por elegir una única zona común. Por ejemplo, la región Purhépecha en el estado de Michoacán (capítulo IV) se divide entre las zonas 13N y 14N, cuyos meridianos centrales son -105 y -99 respectivamente. Por convención, se utilizó la zona 13N para toda la región.

Figura AIII.4. Zonas y fajas UTM para México.



Fuente: Guevara *et al.*(2006). Notas: Por convención, cada una de las zonas se divide en fajas transversales de 4 grados de latitud, a México le corresponden las fajas D a I. Para establecer una referencia podemos considerar que un grado equivale aproximadamente a 110 km.

ANEXO IV: Lista de estudios de caso sobre uso de leña en México

La siguiente lista bibliográfica es un primer esfuerzo de una compilación exhaustiva de estudios de caso sobre uso de leña en México. Las referencias están siendo incorporadas en una base de datos georeferenciada que permitirá superponer las localidades y áreas de estudio de cada trabajo con variables espaciales (e.g. número y tipo de estudio por eco-región).

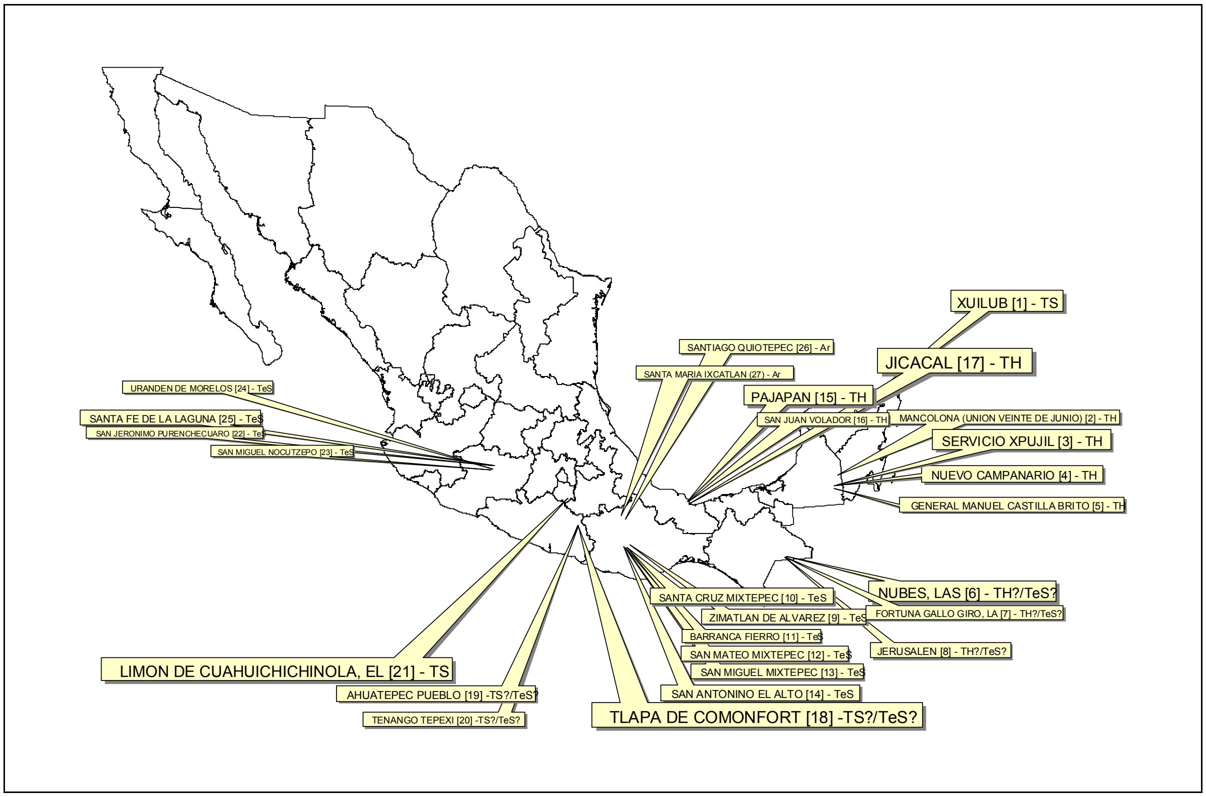
La base de datos georeferenciada, como cualquier otra base de datos no-espacial, va a servir como una plataforma de consulta ya que para cada trabajo se cuenta con 1) variables que reporta (e.g. consumo per cápita, especies preferidas, tiempo destinado a la recolección, etc.), 2) tipo de trabajo (artículo, tesis, reporte, etc.), y 3) formato y disponibilidad de copias.

Mi intención como autor de la base de datos es que sea de dominio público y que reciba actualizaciones, comentarios y correcciones permanentes de los que trabajamos en México con el tema de la leña.

Durante el próximo año (2009) se espera poder ampliar la base de datos con módulos dedicados a la a) producción y consumo de carbón vegetal en México, b) existencias y productividad de biomasa (estudios de caso e inventarios), y c) disponibilidad de información espacial para México (imágenes de satélite, clasificaciones, ortofotos, etc.).

A modo de ejemplo visual, la figura AII.1 muestra la distribución de 28 localidades donde se recopiló información sobre uso de leña por el sector residencial. Los resultados fueron publicados en 11 trabajos, ya incluidos en la base de datos. Se espera que la lista de localidades contempladas en el total de estudios de caso conducidos en México sea demasiado extensa para ser representada en un único mapa con cobertura nacional.

Figura AIV.1. Ubicación de 28 localidades analizadas en 11 estudios de caso sobre uso de leña en México.



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ANEXO V: Artículos directamente relacionados con los resultados de esta Tesis

A.V.1 Why current assessment methods may lead to significant underestimation of GHG reductions of improved stoves

A continuación se adjunta el artículo publicado en la revista *Boiling Point*, Nº54, año 2007.[42]

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[42] Se puede obtener una copia en formato PDF del artículo desde la página Web de la revista: http://www.hedon.info/goto.php/BoilingPoint. Todos los artículos de la revista son de libre acceso, sin embargo, si tuviera algún problema, favor de contactarse con aghilardi@oikos.unam.mx y le será enviada una copia en formato PDF a la brevedad.

Why current assessment methods may lead to significant underestimation of GHG reductions of improved stoves

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The inclusion of improved stove programmes in carbon trading schemes requires valid methods for estimating their impact on greenhouse gas emissions. Current approaches often make use of IPCC default emission factors or those from controlled water boiling tests (WBT), yet little is known about whether these emission factors are representative of normal daily stove use. This article compares the use of IPCC and WBT-derived emission factors with those measured in homes during normal daily stove use and found that both the IPCC and WBT-derived emission factors resulted in substantially underestimating the carbon savings achieved from the installation of a Patsari improved stove in rural Mexico. It also evaluates using community-level fuel renewability estimates in the calculation of carbon savings and looks at the carbon savings that can be made using this factor

Introduction

There is a growing interest in the potential to trade carbon offsets from improved stove programs on carbon markets for voluntary reductions, or as part of international accords. To include improved stoves in these trading schemes, methods meeting minimum accountability standards for quantifying their impact on GHG emissions are needed. Such methods are especially important given that 2 billion people in the developing world still rely on biomass for cooking and, depending on fuel renewability, up to the equivalent of 10 tonnes of carbon dioxide may be saved per household per year with an improved stove (Johnson et al., 2007).

Calculating carbon emissions from stoves incorporates at least five key parameters: stove adoption rates, stove maintenance, fuel consumption, emission factors, and fuel renewability where biomass is the main energy source. This article focuses on methods for deriving emission factors and renewability since they are not well established. Experience in rural Mexico indicates that using IPCC emission factors or emission factors from controlled laboratory tests instead of emission factors measured during normal daily stove use, are likely to lead to significant errors in estimation of carbon savings. In addition we find that community specific estimates of biomass renewability have the potential to dramatically improve carbon savings estimates.

The Patsari Project

Over 6,000 Patsari improved stoves have been disseminated in Mexico by the non-profit Grupo Interdisciplinario de Tecnologia Rural Apropiada (GIRA - www.gira.org.mx), of which 2,500 are in Purépecha communities in the central Mexican highlands. The Patsari Project, which received a 2006 Ashden sustainability award for Health and Welfare (www.ashdenawards.com), incorporates community-based monitoring and evaluation of the overall impacts of the Patsari improved stove. This includes studies on health, indoor air pollution, stove adoption, social perception, fuelwood renewability, energy performance, and greenhouse gas (GHG) emissions. The primary goal of the GHG study was to demonstrate and validate approaches for the quantification of GHG emissions from traditional and Patsari stoves in rural Purépecha communities, which could be applied on a wider scale. The results provided the quantitative basis for subsequent trading of carbon offsets from the project in carbon markets.

Estimation of GHG emissions from cooking in rural communities

The majority of cookstove emission factors have been derived using controlled testing procedures in simulated kitchens (e.g Smith et al., 2000; Zhang et al. 2001), due to the complexity of applying standard measurement techniques in homes. The most commonly used controlled testing procedure has been the Water Boiling Test (WBT). Since the bulk of current stove emissions knowledge comes from research using the WBT, current IPCC stove emission factors and those often cited in emissions inventories for climate modelling are ultimately derived from the WBT. However, little formal testing has been conducted to evaluate if the WBT produces emissions representative of those from cookstoves in homes during normal daily activities. In Mexico the relationship between using emission factors from the IPCC, WBTs, and normal daily stove use in homes were evaluated for both traditional open fire stoves and improved Patsari stoves (see Figure 1).

Nominal combustion efficiency (NCE), or the amount of fuel carbon converted to CO_2, during WBTs in the simulated kitchen was found to substantially over predict the efficiency of open fires (Figure 2). NCEs produced during WBTs in a simulated kitchen also indicated the mud-cement Patsari was 7% less efficient than traditional open fires, while the converse was true in homes during normal stove use by local residents, where the mud-cement and brick Patsaris were 2.6 and 7.9% more efficient, respectively. Thus using the WBT for cookstove GHG estimates in these communities would result in erroneous emissions levels.

This result is not entirely surprising given that the Patsari was designed primarily for tortilla cooking, which ac-

Figure 1. Traditional open fire (A), mud-cement Patsari (B), and brick Patsari (C) (Photo: M. Johnson)

counts for half of fuel consumption in rural Mexico, rather than boiling water. An energy performance study by Berrueta et al. (2007) found the Patsari used approximately twice as much fuelwood as open fires during the high power boiling phase of the WBT, yet required 44-57% less fuelwood per tortilla in controlled cooking tests. In agreement with the combustion efficiency results, Berrueta et al. (2007) also found the Patsari reduced household fuelwood consumption by 48-66% during kitchen performance tests, further confirming that local stove use practices diverge significantly from WBT burn cycles.

Similar results are obtained when comparing global warming contributions, where the CO$_2$-equivalent carbon savings from an improved cookstove can be underestimated by up to 64% (Figure 3). Emission factors of gaseous species[1] were converted to CO$_2$-equivalent using IPCC 100-year global warming potentials, then combined with fuel use estimates from Berrueta et al (2007) assuming that 80% of the fuelwood was harvested renewably (see below). For both gases included in Kyoto protocols (CO$_2$ and CH$_4$) and a more expanded set (CO$_2$, CH$_4$, CO, and TNMHC[2]), carbon savings of the Patsari were significantly underestimated by both WBT and IPCC default emission factors, although the latter do not differentiate by stoves and are therefore solely a function of reduced fuel consumption.

In addition to the erroneous carbon estimates, Figure 3 also shows the significant fraction of mitigated carbon emissions from the use of household improved cookstoves that is not included when only Kyoto Protocol sanctioned gases are considered, due to the large fraction of carbon that is diverted into other GHGs. For residential cook stoves, therefore, all GHGs should be included, especially as non-inclusion of some of the gases can lead to wrong conclusions about the relative benefits of different stove types (Edwards et al., 2004).

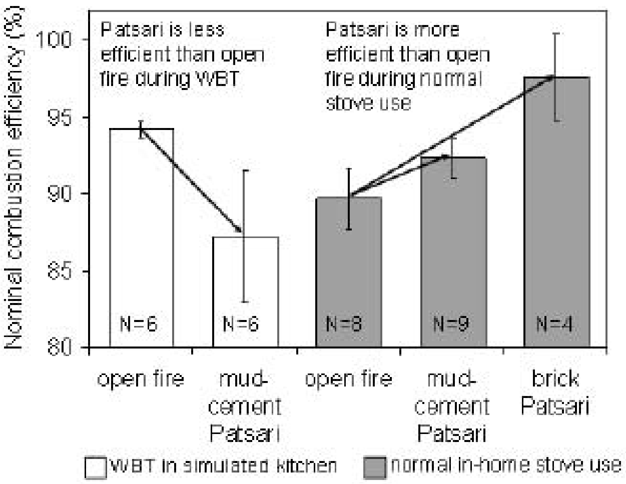

Figure 2: Nominal combustion efficiency of stoves during WBTs and in-home stove use. Arrows highlight that WBT resulted in open fires producing higher NCEs than Patsaris, when the converse was found to be true under normal daily stove use.

WISDOM and renewability

For biomass combustion, fuel renewability is a critical component in calculating carbon emissions since the CO$_2$ that is reintegrated into the next cycle of vegetative growth must be subtracted from the original emissions. The difference in emissions assuming renewable compared to non-renewable biomass use far outweighs the differences between stove types, and so accurate estimation is critical in assessing carbon savings (Edwards et al, 2004). Wood fuel renewability in the Purépecha region was estimated using WISDOM (Woodfuel Integrated Supply/Demand Overview Mapping model) (Masera et al., 2006; Ghilardi et al., 2007), a GIS-based model that spatially integrates fuel wood supply and consumption, and has been applied in several countries. The supply of fuel wood is estimated on a village basis by defining accessible areas through cost-distance maps and other GIS techniques, and combined with data on land cover classes, land cover change and fuel wood productivity. Fuel wood demand comes from local surveys, case studies and geo-referenced population censuses, and includes indica-

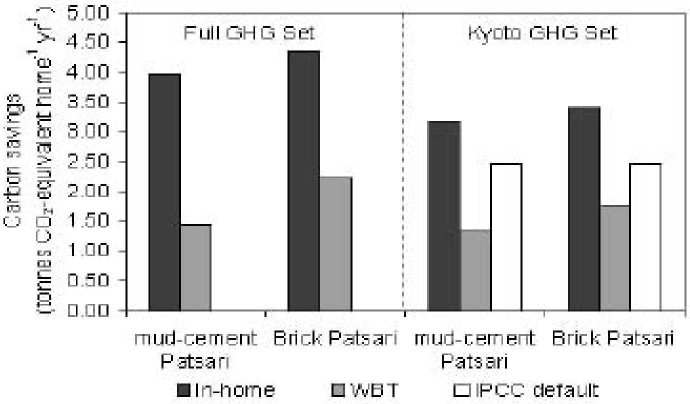

Figure 3: Carbon savings per home using in-home, WBT, and IPCC emissions factors. Savings were calculated assuming 80% fuel renewability for the Purépecha region (Ghilardi et al., 2007) and fuel consumption data from Berrueta et al. (2007). Notes: a. WBT emission factors for brick Patsaris were derived from WBTs conducted within homes rather than in the simulated kitchen. b. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories only report wood emission factors for CO_2 and CH_4 for stationary residential combustion. No CO_2 emission factor is provided for wood stoves and a broad range (258-2190 kg TJ^{-1}) is presented for CH_4. The default value for stationary residential wood combustion was used for CH_4 (300 kg TJ^{-1} [4.8 g kg^{-1} assuming a calorific density of 16,000 kj kg^{-1}]).

tors such as population density, percentage of households using fuel wood and fuel wood consumption by main species. The use of detailed local data allows WISDOM to make consistent renewability estimates at the community level.

Such fine discrimination makes calculating emission reductions on a community basis possible, rather than applying mean regional renewability estimates based on top down surveys. The importance of the renewability component is demonstrated in Figure 4, which presents the carbon savings achieved from replacing an open fire with a mud-cement Patsari under different renewability scenarios. Potential CO_2-equivalent savings under non-renewable harvesting are a factor of 3.7 larger than those assuming renewable harvesting of biomass. The potential for underestimating marketable carbon savings is made evident by the village of Puacuaro, for which WISDOM estimates 15% of fuelwood is harvested renewably, in contrast to the region's mean 80% renewability (see Figure 5). Use of the mean regional renewability in this case would indicate the Patsari saves less than half of that which is achieved using Puacuaro's renewability estimate. Such large error for a single village also demonstrates the importance of community-level renewability data for projects focused in a small number of communities. Additionally, the relatively large carbon savings per household in Puacuaro illustrate WISDOM's potential to maximize GHG reductions by focusing cookstove dissemination efforts in areas with less renewable harvesting of biomass.

Conclusions

Methods have been developed to assess rural residential cookstove GHG emissions that rely on: locally derived GHG emission factors during daily cooking activities, in home assessments of fuel wood savings, and a spatially explicit determination of fuelwood renewability at village level. Results demonstrate the significant potential for carbon savings as a result of installation of the Patsari improved cookstove.

Methodologically, if these results hold true for other stoves and other communities, controlled WBT based emission factors from simulated kitchens should not be used in the estimation of carbon savings from improved cook stoves. Instead, continued efforts should be made to assess emissions from stoves during daily activities in local communities

Finally, differences in carbon savings between non renewable and renewable harvesting are of such magnitude that community based assessments of renewability are critical in assessment of carbon savings, and provide an opportunity for maximizing GHG reductions by focusing cookstove dissemination efforts in areas with less renewable harvesting of biomass.

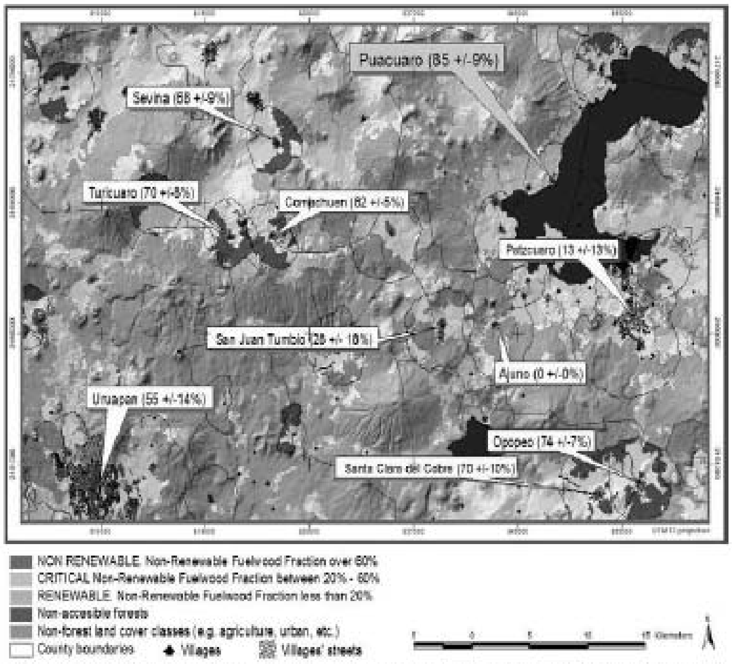

Figure 4. The use of detailed local data allows WISDOM to make consistent renewability estimates at the community level [figures are % non-renewable].

Acknowledgements

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Notes and References

1. Although particulate emissions were made they are not reported here, see Johnson et al., (2007)

2. Total non methane hydrocarbons

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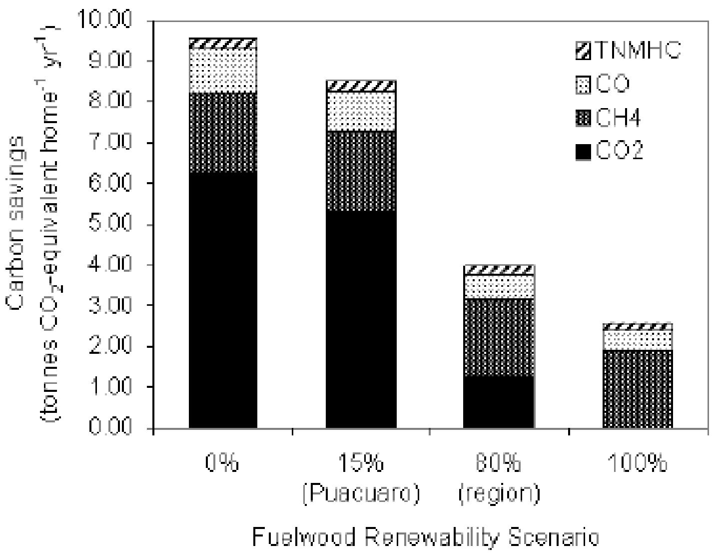

Figure 5. Carbon savings from switching from an open fire to mud-cement Pastari for four renewability scenarios.

Profile of the authors

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A.V.2 An Integrated local-based approach to estimate CO2-equivalent savings from improved biomass cookstoves for carbon offset programs

A continuación se adjunta el artículo enviado a la revista *Environmental Science and Technology*, actualmente bajo revisión por los editores de la revista.

An Integrated local-based approach to estimate CO2-equivalent savings from improved biomass cookstoves for carbon offset programs

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Keywords: greenhouse gas emissions, carbon trading, non-renewable biomass, , improved stoves

Abstract

In spite of growing interest, a principal obstacle to a wider dissemination of improved cookstove carbon offset projects has been the lack of accountability in estimating CO2-e savings, lTo demonstrate that robust estimates of CO2-e savings can be obtained at reasonable cost, an integrated approach of community-based sub sampling of homes to estimate fuel consumption and stove greenhouse gas emissions, combined with spatially explicit community based estimates of the fraction of non-renewable biomass harvesting (fNRB) was used to estimate CO2e-savings for Purépecha communities of Michoacán, Mexico. Mean annual household CO2-e savings for the full set of GHG gases were 4.8 tCO2-e home-1 yr-1 (95% CI ±22%), and for the Kyoto set of gases were 3.9 tCO2-e home-1 yr-1 (95% CI ±25%) respectively, using a mean fNRB harvesting weighted by the number of improved stoves in each community of 39%. CO2-e savings ranged from 2.9 (95% CI ±37%) to 9.6 tCO2-e home-1 yr-1 (95% CI ±17%) for renewable and non-

renewable harvesting in individual communities, respectively. Since emission factors, fuel consumption and fNRB each contribute significantly to the overall uncertainty in estimates of CO2-e savings, community based assessment of all of these parameters is critical for robust estimates. Reporting of the overall uncertainty in the CO2-e savings estimates provides a mechanism for valuation of carbon offsets, which would promote better accounting that CO2-e savings had actually been achieved. Cost of CO2-e savings as a result of adoption of Patsari stoves was US$7 per tCO2-e based on initial stove costs, monitoring costs and conservative stove adoption rates, which is ~ 5 times less expensive than use of carbon capture and storage from coal plants, and ~ 21 times less than solar power. The low relative cost of CO2-e abatement of improved stoves combined with substantial health co-benefits through reduction in indoor air pollution provides a strong rationale for targeting these less expensive carbon mitigation options, while providing substantial economic assistance for stove dissemination efforts.

Introduction

There is growing interest in trading carbon offsets from improved stove programs on carbon markets for voluntary reductions, or as part of the Clean Development Mechanism (CDM) of the Kyoto Protocol . This interest arises from the large number of people that still cook with biomass (approximately half of the global population) [1], and because emissions of greenhouse gases (GHGs) relative to delivered energy are high as a result of poor total energy efficiency of traditional devices. There are three principal barriers to more widespread acceptance of carbon offsets from improved biomass cook stove projects. Firstly, measurement and verification of emissions reductions is complex compared to the stack monitors typically used for industrial facilities as stoves are spread over large spatial areas, often in remote regions. Traditional assessment methods are also invasive, requiring installation of vented hoods in homes, and costly, using sophisticated instrumentation and analysis that far exceed the value of carbon offsets in each home, and typically provide only short-term estimates of emissions for a single meal event. Secondly, although in more commercial sectors measuring fuel consumption is relatively easy, , cook stoves often rely on non-commercial or locally purchased fuels, and tracking of fuel consumption presents several methodological and logistic challenges [2]. Thirdly, for biomass burning stoves the tools to consistently estimate the fraction of non-renewable biomass (fNRB) harvesting have been lacking. Consistent fNRB estimates are critical to accountability due to the magnitude of the difference in CO2-equivalent (CO2-e) savings between renewable and non-renewable harvesting of fuel wood [3]. Thus, while the idea of estimating carbon offsets derived from the replacement of traditional cooking devices a more efficient cook stoves is conceptually simple, monitoring of CO2-e emissions, fuel use and fNRB combined with the tracking of stove use is actually very challenging As a result typical assessment methods for small-scale residential cookstove projects have made use of indoor air concentrations, rather than emissions, combined with default IPCC emission factors [Bailis et al], or have used emissions factors from water boiling tests in simulated kitchens [venkataraman and Rao, 2001, Zhang and Smith 1996], which do not reflect daily cooking activities [6]. Local community-based sub sampling of fuel consumption and emission factors during daily cooking activities combined with spatially explicit community based estimates of fNRB to derive robust estimates of CO2-e savings, and associated uncertainty, have not been undertaken.

Given the increasing interest in carbon offset projects, It has become increasingly clear that rigorous methods are required to calculate these offsets that will stand up to international scrutiny. Perhaps more importantly, the value of carbon traded on international markets is intrinsically linked to confidence in the estimates. Since the level of information available for each project will likely vary, the confidence bounds of carbon offset estimations will need to be explicitly defined, so that they may be reflected in carbon pricing. Unfortunately, however, IPCC default emission factors do not allow such computation, as uncertainty is not reported. Explicit reporting of confidence bounds of carbon offsets would provide a mechanism for inclusion of improved stove projects that have other positive economic, environmental and health benefits in rural communities.

In the current paper CO2-e savings are assessed for households that switch from traditional open fire stoves to improved Patsari stoves in the Meseta Purépecha region of central Mexico, using local community based assessments of fuel consumption and fNRB combined with estimates of emission factors during daily cooking activities. Overall uncertainty associated with CO2-e savings estimates is evaluated in relation to both uncertainty and monitoring cost for optimization of sub sampling design. Further, net costs of making these CO2-e savings are estimated and compared to current carbon mitigation technologies in industrialized nations. Finally, we propose a relatively simple and economical method using two gaseous species to verify emissions reductions in statistical sub-samples that do not involve installation of hoods or the complex analytical requirements of previous emissions assessments.

Methods

Standard statistical approaches can be applied to limited sub-samples to estimate CO2-e savings in larger populations of homes with improved stoves, and provide the confidence intervals surrounding the estimate. Thus using standard statistical criteria, CO2-e savings for the larger population can be determined with greater than 95% probability of lying within the confidence bounds of the estimate, after including variability associated with each step in the estimation: emissions measurements, fuel consumption, and the fNRB harvesting.

Estimation of emission reductions

Reductions in emissions of greenhouse gases expressed in CO2-e home-1 yr-1 may be calculated as follows:

$$\Delta CO_2e = \sum_{i=1}^{n} (EF_{Ri} \times FC_i[1 - fNRB]) + (EF_{NRi} \times FC_i[fNRB]) - \sum_{j=1}^{n} (EF_{Rj} \times FC_j[1 - fNRB]) + (EF_{NRj} \times FC_j[fNRB]), \quad (1)$$

where EF is the emission factor in CO2-e per ton fuel consumed, FC is fuel consumption in tons per year, and fNRB is the fraction of non-renewable biomass use. Emission factors assuming non-renewable harvesting (EFNR) and renewable harvesting (EFR), which exclude CO2, are applied to the respective fraction of non-renewable and renewable fuel consumption. The change in emissions is calculated based on the sum of emissions for the different stoves used in homes with the improved stove (j) subtracted from the sum of emissions for the different stoves used in homes with traditional stoves (i). Emissions reductions were calculated on a per residence as multiple stoves are often observed in homes, with traditional stoves still being retained for some cooking tasks and the installation of an improved stove impacting fuel consumption of other stoves [7-9].

Estimation of emission factors

Emissions of greenhouse gases were assessed in homes during normal cooking activities for a random sample of 8 open fire and 13 Patsari stoves. Full description of the sampling methodology and QA-QC is presented in Johnson et al. (2008). Briefly, emissions were sampled into a 100 L light-shielded Tedlar bag (SKC Inc, USA) with an SKC universal pump (model 224-PCXR8, SKC Inc., USA) at a flow rate of 0.86 l min-1. Following the sampling period, approximately 2-3 liters of the initial sample in the Tedlar bag were transferred to a 5 L metal-coated multiple-layer Tedlar (MMT) bag for storage until gas chromatography analysis. CO2, CO, CH4, and total non-methane hydrocarbons (TNMHC) were quantified using a Perkin Elmer 8410 gas chromatograph (Perkin Elmer, Waltham, MA) with a flame ionization detector, and a nickel catalyst methanizer (SRI Instruments, USA). A 80-100 mesh Carbosphere® packed stainless steel column (Waters Associated, Inc., USA) was used to separate CO2, CO and CH4 analyses and a glass bead stainless steel column (Alltech, USA) used for total non-methane hydrocarbon (TNMHCs) analysis. Quantification was made using 7-point calibration curves (r2 >0.995) from a NIST-traceable gas standard mixture of CO2, CO, and CH4 in a helium balance (Scott Specialty Gases, USA).

Each GHG species was converted into CO2-e using 100-yr GWPs published by the IPCC [11,11]. N2O was not included in this analysis and has been shown to be a negligible fraction of CO2-e emission from biomass stoves as it is associated with higher temperature combustion [12,13]. Unlike voluntary markets, which can include a more extensive set of GHG species, estimation of emissions for carbon offset programs under the Clean Development Mechanism of the Kyoto protocol are restricted to CO2 and CH4. Emission reduction scenarios for both Kyoto-sanctioned gases (CO2 and CH4), and a more comprehensive set (CO2, CH4, CO, and TNMHC) are presented.

Estimation of fuel consumption

Fuel consumption was assessed using kitchen performance tests, in which daily consumption patterns and cooking tasks were monitored in community households over a over a 7-day period both before and after the introduction of Patsari cookstove [9]. 23 households using fuelwood and 20 households that used a combination of fuelwood and LPG were selected randomly from a community intervention study in two communities of the Meseta Purépecha: Comachuén and La Mojonera. In all households the main fuelwoods were oak and pine, which were not provided to families to minimize bias in family fuel consumption. To obtain fuel consumption per capita, an equivalence factor called a standard adult was used, which relates the fractional food requirement (and energy needed to cook the food) for a child, woman or elderly person to that of an adult man of reproductive age.

Estimation of the fraction of non-renewable fuelwood harvesting

Community based estimates of the non-renewable fraction of fuelwood harvesting in the Purépecha region was estimated using WISDOM (Woodfuel Integrated Supply/Demand Overview Mapping model) (Masera et al., 2006; Ghilardi et al., 2007), a GIS-based model that spatially integrates fuelwood supply and consumption. Community based estimates of the non-renewable fraction of fuelwood harvesting were used as national or regional level estimates lack sufficient resolution to characterize fuelwood consumption for specific communities, the functional scale required for small scale carbon offset projects. In order to determine the non-renewable fraction of fuelwood harvesting, the balance between fuelwood supply and demand is needed. The supply of fuelwood is estimated on a village basis by defining accessible areas from which residents obtain fuelwood, which integrates into a cost-distance map with key topographical features, the spatial distribution of different land-use land-cover classes as well as their fuelwood productivity, and the average daily time spent for collecting fuelwood (Ghilardi et al., 2008). Fuelwood demand is estimated from local surveys, and geo-referenced population censuses, and includes indicators such as population density, percentage of households using fuelwood and fuelwood consumption by main wood species (refer to Ghilardi et al., 2008 for more details). The use of detailed local data allows WISDOM to make consistent renewability estimates at the community level, with confidence bounds derived from propagating uncertainty contributed by each component.

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

$$\mathrm{FWSv} = \sum_{j=1}^{10} (A_{vj} * P_j) , \qquad (2)$$

where FWSv is the amount of fuelwood which can be sustainably harvested from each locality accessible area “v”, in Mg yr-1 (dry matter); Avj is each locality accessible area “v” by land cover “j” in ha and Pj is the fuelwood productivity by land cover class “j” in Mg ha-1 yr-1 (dry matter), The fraction of fuelwood extracted on a non-renewable basis was estimated based on the following equation:

$$\text{fNRBv} = \left|\frac{\mathrm{FWS_v - C_l}}{\mathrm{C_l}}\right|, \quad (4)$$

where fNRBv is the fraction of fuelwood extracted on a non-renewable basis per locality accessible area “v”, as a ratio or percentage for FWSv< Cl and NRFWv=0 for FWSv ≥0; and Cl is the fuelwood consumption per locality “l”, following a baseline scenario (i.e. fuelwood consumption calculated based on open fires, in Mg yr-1 (dry matter).

Estimation of uncertainties

Standard errors for emission factors, fuel consumption, and fNRB used in the carbon reductions calculation (Equation 1) were estimated with:

$$\mathrm{SE_x} = \frac{\mathrm{SD_x}}{\sqrt{\mathrm{N_x}}}, \quad (5)$$

where SEx is the standard error, SDx is an estimate of the population standard deviation, and Nx is the sample size for each respective component. The variances and sample sizes for emission factors and fuel consumption are those reported by Johnson et al. (2008) and Berrueta et al. (2008) with fuel consumption data weighted to reflect 83% exclusive wood users and 17% mixed wood/LPG users determined by tracking stove usage. The fNRB for each of the 25 communities was weighted by the number of stoves in each community to estimate the mean fNRB for the 603 stoves. The sample size for fNRB was determined as the number of homes in the sub-sample where fuel consumption estimates were combined with the fraction of non-renewable harvesting to estimate CO2-e savings.

Propagation of error in estimates of CO2-e savings were determined using:

$$\mathrm{SE_s} = \sqrt{\sum_{i=1}^{n}\left(\frac{\delta \mathrm{SE_s}}{\delta x_i}\frac{\mathrm{SD}_{x_i}}{\sqrt{\mathrm{N}_{x_i}}}\right)^2}, \quad (6)$$

where SEs is the standard error of the CO2-equivalent savings. 95% confidence intervals for CO2-e savings were then estimated using:

$$95\%\ \mathrm{CI_s} = \mathrm{SE_s}(1.96), \quad (7)$$

where CIs is the 95% confidence interval for the CO2-e savings, SEs is the propagated standard error derived using Equation 6, and 1.96 is the z-value assuming an alpha significance level of 0.05. All terms were assumed independent and thus covariance was not included in the standard error estimates of CO2-e savings. Estimation of the contribution of individual variables in Equation 1 to the standard error of CO2-e estimates were computed by dividing the square of each component's respective partial derivative by the sum of the squared partial derivatives.

Simplified Monitoring Procedure

Two monitoring techniques were tested to further simplify the field measurement of emission factors.

Monitoring open fires with a sampling probe

A main obstacle for in-home emissions monitoring has been the need for intrusive and cumbersome constant flow sampling hoods to control for dilution effects of room air on gas concentrations in the plume. To determine if a simple probe could replace sampling hoods, CO2/(CO2+CO) ratios monitored using a 3-pronged probe that hung directly above an open fire were compared against CO2/(CO2+CO) ratios measured with a constant flow sampling hood. Samples were taken at 30 second intervals alternating between the hood and probe for three separate open fires.

GHG Emission Factor estimation using CO2/(CO+CO2) ratios

If CO2-e savings assessments are to be performed by non-specialist groups, accessible and economical methods are required that do not involve complex analytical techniques typical of emissions assessments. One approach suggested by Edwards et al. (2003) is to use the CO2/(CO2+CO) ratio, for which a variety of relatively low cost real-time instrumentation exists, as a proxy for nominal combustion efficiency (NCE) to estimate emissions of GHGs, as the relative emissions of individual GHG species for a given fuel type are largely determined by combustion efficiency [14]. This approach was evaluated by simultaneously monitoring CO and CO2 concentrations with a flue gas analyzer (Autologic, USA) in the homes in which the gas chromatography analysis was conducted. The instrument was calibrated with NIST-traceable CO and CO2 reference gas (Scott Specialty Gases, USA) and background concentrations were accounted for by zeroing the unit in room air for a minimum of 5 minutes before and after sampling.

Results

Figure 1 shows annual CO2-e savings with corresponding 95% confidence intervals for residences adopting an improved Patsari stove using locally assessed emissions factors, fuel consumption and fNRB harvesting in local Purepecha communities).

Mean annual household CO2-e savings for the full set of GHG gases were 4.8 tCO2-e home-1 yr-1, and for the Kyoto set of gases were 3.9 tCO2-e home-1 yr-1 respectively, using a weighed mean fNRB harvesting of 39%(Table 1). CO2-e savings and 95% confidence intervals are shown for the entire range of 0-100% non-renewable harvesting as CO2-e as savings in individual communities vary widely within the Region (Figure 2). Since CO2-e savings ultimately should be estimated on a community basis, Figure 1 also demonstrates the range of potential carbon savings across fNRB scenarios, and how increased value of CO2-e savings would tend to focus offset projects in communities with greater resource constraints and environmental impacts, which may also favor improved stove adoption due to perceptions of fuel availability or cost. Mean CO2-e savings and corresponding 95% confidence intervals using the full set of GHG gases ranged from 2.9 tCO2-e home-1 yr-1 (95% CI ±37% or ±1.1 tCO2-e home-1 yr-1) for renewable harvesting of fuelwood, to 9.6 tCO2-e home-1 yr-1 (95% CI ±17% or 1.6 tCO2-e home-1 yr-1) for non-renewable harvesting of fuelwood. Corresponding CO2-e savings and 95% CI using the Kyoto set of GHG gases ranged from 2.1 tCO2-e home-1 yr-1 (95% CI ±48% or ±1.0 tCO2-e home-1 yr-1) for renewable harvesting of fuelwood to 8.2 tCO2-e home-1 yr-1 (95% CI ±18% or ±1.5 tCO2-e home-1 yr-1) for non-renewable harvesting of fuelwood, respectively.

Propagating the uncertainty from estimation of each component in the CO2-e saving calculation (Equation 1) resulted in overall 95% confidence intervals around the mean CO2-e savings estimate of 22% (±1.0 tCO2-e home-1 yr-1) using the full set of GHG gases and 25% (±1.0 tCO2-e home-1 yr-1) using the Kyoto set. The majority of uncertainty in mean CO2-e savings using the full set of GHG gases was contributed by emission factors for open fires (21%), open fire fuel consumption (24%), and fNRB (48%). Incomplete accounting of greenhouse gases from relatively inefficient household stoves using the Kyoto set of gases resulted, therefore, in a 19 % reduction in mean CO2-e savings relative to the full set of GHG gases.

The relative contributions of emission factors, fuel consumption and fNRB to overall uncertainty in CO2-e savings vary across the range of fNRB harvesting in communities where the stove was disseminated, illustrating how local community based assessment of all of these components is critical for estimating CO2-e savings in areas where fNRB is so heterogenous across communities. As harvesting of biomass gets more renewable and CO2 emissions are not included in estimation of CO2-e savings (as it is taken up by plants in the next growing cycle) uncertainty associated with fuel consumption contributes less to the overall uncertainty in the estimate of CO2-e savings (as CO2 represents the largest fraction of carbon emissions from fuel mass), and the emission factor and renewable status of harvesting dominate uncertainty. Conversely, as a greater fraction of the harvesting of biomass is non-renewable, fuel consumption and emissions begin to dominate the overall uncertainty in the estimate of CO2-e savings relative to fNRB, with the transition point around 60% for the full set of GHG gases. Fuel consumption and emission factors for secondary open fires and use of additional LPG stoves contributed 1% or less towards the CO2-e savings standard error for all fNRB scenarios.

The confidence interval surrounding the mean estimate of CO2-e savings is dependent on the number of homes sampled. Statistical sub samples must be selected that balance the sample size demands to provide rigorous estimates of CO2-e savings and the cost incurred in validation, so that costs do not exceed the value of the CO2-e savings. Table 3 shows the sample sizes to assess emissions factors and fuel consumption. In addition, if CO2-e savings assessments are to be performed by non-specialist groups or need to be further simplified, approaches that do not involve the complex analytical requirements of previous emissions assessments are required. To simplify monitoring strategies by removing the requirements for constant flow emissions hoods, figure 3 shows the relationship between CO2/(CO2+CO) ratios monitored using a 3-pronged probe that hung directly above an open fire compared against CO2/(CO2+CO) ratios measured with a constant flow sampling hood for three open fires, and the relative uncertainty introduced by these estimates. Correlation between CO2/(CO2+CO) ratios had an r2of 0.98 ($p<0.001$), with a slope of 0.98, demonstrating good agreement between the measures. Similarly, to simplify monitoring techniques that could be deployed by non-specialist groups, Figure 4 shows the relationship between CO2/(CO2+CO) ratio using portable commercial instruments that do not involve complex analytical requirements and NCE determined using gas chromatography for emission factors during normal daily cooking activities using both open fire and Patsari stoves. The correlation between NCE and CO2/(CO2+CO) ratio had an r2 of 0.98 ($p<0.001$) for open fires and 0.94 ($p<0.001$) for Patsaris, demonstrating that the CO2/(CO2+CO) ratio was a good proxy for NCE for the fuels used in these homes. Since relative amounts of products of incomplete combustion and thus CO2-e emissions are related to NCEs, Table 2 shows CO2/(CO2+CO) ratios can predict CO2-e emissions. Char is also included as a predictor for non-renewable models because each gram of fuel that is converted to char negates a gram of fuel from being emitted as CO2 or PICs, of which ~90% of fuel carbon or greater is emitted as CO2. Since CO2 is the largest contributor to CO2-e emissions for non-renewable fuel use, and excluded from CO2-e emissions for renewable fuel use, char production is only a significant predictor for non-renewable scenarios.

Discussion

Typical assessment methods for small-scale carbon offset projects using default IPCC emission factors combined with regional estimates of fuelwood renewability result in significant errors in CO2-e savings. Firstly, current databases of emissions factors were derived from controlled tests in simulated kitchens for a limited number of stove combinations primarily in India and China, and do not reflect actual emissions from homes during daily cooking activities [6]. Perhaps more importantly the differences are not consistent between stove types. For example, open fire combustion efficiency is overestimated while Patsari combustion efficiency is underestimated by water boiling tests in simulated kitchens relative to during normal daily stove use, which would result in a 64% underestimate of CO2-e savings [3]. In addition the variability in the individual emissions factors is not reported in current databases making it impossible to estimate uncertainty in overall CO2-e savings. Use of emissions estimates that are not derived from local community based sub samples, even if derived from measurement in real homes during daily cooking activities, would still require broad assumptions about stoves, fuel types, cooking activities, stove conditions and combustion efficiencies leaving aside variations as a result of altitude, seasonal and meteorological factors. For emissions factors and fuel consumption, therefore, local community based data is critical in reducing uncertainty in CO2-e savings estimates.

Similarly, use of region wide estimates of fNRB based on rough average productivities of land cover classes and average consumption do not have sufficient resolution to accurately estimate the actual impact of fuelwood harvesting at the local scale required for carbon offset projects. (WE CAN cite two case studies here Ghilardi et al., 2007; Top, N., Mizoue, N., Ito, S., Kai, S., 2004. Spatial analysis of woodfuel supply and demand in Kampong Thom Province, Cambodia. Forest Ecology and Management 194, 369-378.) As shown in our study area, this procedure may lead to significant errors when estimating CO2-e savings and respective confidence intervals. Figure 5 shows the difference between fuelwood supply-demand balance estimates for the same communities of the Meseta Purépecha using a region wide approach versus a community based assessment of fNRB. The regional approach estimates a balance of 647 Mt ± 785, while using the community-base assessment we get 64 Mt ± 73. In general,
region wide approaches overestimate fuelwood supply , as they do not take into account non-accessible areas, land ownership and local topography, and result in greater variability as a result of less explicit land use and vegetation cover. Since fNRB harvesting varies widely even between adjacent communities, and small-scale carbon offset projects in the household sector are not equally distributed in all communities throughout a region, fNRB harvesting estimates should be based on community level assessment.

Confidence in CO2-e savings estimates

Use of the more constrained Kyoto GHG set resulted in a reduction of 26% in CO2-e savings relative to use of the full set of GHGs. Although differences in CO2-e emissions estimates between the Kyoto and full GHG set are much smaller for centralized fossil fuel energy generation in industrialized nations where combustion efficiencies are much higher, for inefficient combustion in small scale devices the full range of GHGs should be included to avoid issues of incomplete accounting [15].

Although carbon reductions from small-scale household energy projects have been traded on voluntary markets, a principal criticism of these offsets has been the lack of accountability and verification that the CO2-e savings have actually been achieved [4,5]. In part this has been because relatively non-invasive methods to verify emission reductions in homes during daily activities and methods for consistent spatially explicit community based estimates of fNRB harvesting have been lacking. Equally critically, carbon offset estimations have been reported without the corresponding uncertainty in the estimate. Although calculation of CO2-e savings involves combination of emission factors, fuel consumption and fNRB estimated with different methods, standard statistical approaches can be applied to propagate each component's respective uncertainty in estimating the overall 95% carbon offset confidence intervals. Reporting these confidence intervals provides a quantitative measure of confidence in the estimate, which shows significant potential to be used in valuation of CO2-e offsets. Since resolution and quality of information from individual projects is likely to differ, valuation of CO2-e offsets based on the confidence bounds of the estimate provides a mechanism to reward organizations marketing offsets where more time and energy has been committed to verifying the carbon offset estimates, without excluding those where such information gathering is limited, but may provide valuable areas for carbon reduction. From a climate perspective this would promote better accounting that CO2-e savings had actually been achieved. Given the financial sums potentially involved in future carbon trading, reporting the confidence in the estimate will become more critical for global carbon markets, particularly in preventing unscrupulous practices.

Sub-sampling for CO2-e savings estimation

Unlike the residential sectors of industrialized nations where CO2-e consumption can be assessed by combining commercial energy usage with stack monitored emissions from central power generating facilities, measurement of solid fuel consumption and individual emissions from all homes in rural areas of developing nations is cost prohibitive given the large numbers of stoves and often remote areas involved. Estimating CO2-e savings and corresponding confidence intervals for improved stove projects therefore involves statistical sub sampling of fuel consumption and emissions factors from both traditional and improved stoves to obtain an estimate of both the central tendency and variability in the larger population of homes for which the CO2-e savings are being estimated. Prior to this study the major barriers to field measurement of statistical subsamples for CO2-e savings estimation were the large intrusive sampling hoods, and the analytical methods required for analysis. Since community based estimates of emissions factors are critical in reducing uncertainty of CO2-e savings, relatively inexpensive field based methods are required to assess emissions in homes during daily activities. Figure 3 demonstrates that use of simple sampling probes for open fires and stoves without flues can be used comparably to constant flow sampling hoods, and that stoves with flues can be sampled directly, as fugitive emissions were a minor component of total emissions.

Confidence in CO2-e savings for the larger population can be increased by monitoring larger sub-samples, but a tradeoff exists between increasing confidence in the CO2-e savings and the added costs of monitoring more homes, especially if carbon trading pays for the costs of verification. Figure 6 shows the tradeoff between cost and confidence in CO2-e savings in relation to number of homes monitored for fuel consumption and emissions. For comparison fNRB harvesting of 10% and 50% are included, which show similar trends, although areas with lower fNRB would require larger sample sizes to achieve the same relative confidence in CO2-e savings. This figure highlights the tradeoffs in cost based on our experiences in Michoacan, Mexico. While the magnitude of monitoring costs may vary between different groups and regions, the overall shape of the curve is likely to be similar, and reflect similar tradeoffs with increased confidence in CO2-e savings. Based on these figures the maximum benefit in confidence of CO2-e savings for the lowest cost lies in taking sub samples of 20-30 homes. As shown in Table 3, monitoring 25 homes would reduce the standard error for each emission factor and fuel consumption variable to less than 10%, giving an 95% confidence interval around mean CO2-e savings of ±18% (an 18% decrease in uncertainty relative to the community sub samples presented here).

Although variability of fuel consumption and emissions in other project situations may differ, in the absence of better data, these sample size estimates provide a reasonable starting point. Clearly, however, determination of the number of homes to sub-sample is both driven by whether the sample is likely to capture the overall variability of the larger population and logistical and cost constraints. Valuation of CO2-e offsets based on the confidence bounds of the estimate, therefore, could provide a mechanism whereby increased costs of more rigorous and robust estimation methods are defrayed by increased value of the CO2-e savings.

If CO2-e savings assessments are to be further simplified , approaches that do not involve the complex analytical requirements of previous emissions assessments are required. Based on approaches developed by Edwards et al. (2003), Figure 4 demonstrates that portable commercial instruments to measure the CO2/(CO2+CO) ratio can be used effectively to estimate NCE for oak and pine fuels, which can be used to predict resultant CO2-e savings (Table 2). Model predictions had r2 values ranging from 0.79-0.95 for the full GHG set, but were slightly lower (0.65-0.90) for the more restricted Kyoto gases and renewable harvesting (essentially a prediction of methane emissions from combustion). Uncertainty introduced by use of these models resulted in a 7% increase in 95th percentile confidence intervals of CO2-e savings using the full set of GHGs for Patsaris in the Meseta Purepecha with 39% fNRB harvesting. Over the range of 100% to 0% fNRB harvesting use of these models results in a 3-13% increase in 95th percentile confidence intervals of CO2-e savings for the full set of GHGs. The largest increase in uncertainty occurs for 0% fNRB when the renewable open fire emission factor, which has a relatively low r2 value of 0.79, contributes 46% of the uncertainty in carbon savings (see Figure 1a). This approach therefore shows considerable promise as an inexpensive verification tool. Clearly, however, as the relationship between the CO2/(CO2+CO) ratio and products of incomplete combustion may vary depending on fuel type, use of the CO2/(CO2+CO) ratio to estimate emissions requires calibration with fuel types of interest. Charcoal for example emits a greater fraction of CO than hydrocarbons in relation to fuelwood burning, thus the slope and intercept will be different when using CO2/(CO2+CO) ratio to estimate CO2-e emissions. Thus this approach is perhaps better suited as a verification tool for CO2-e savings in successive time periods after initial verification using direct monitoring of greenhouse gas emissions is performed. Carbon mitigation cost-effectiveness

The monitoring costs, would reasonably be expected to cost less than 20% of CO2-e savings for a project size of 600 stoves, assuming 39% fNRB, carbon price of $15 per tCO2-e and a project timeframe of 7 years.

Carbon prices for emission permits under a cap and trade system designed to meet Kyoto Protocol reduction targets have been estimated at US$26-159 and US$53-68 per tCO2-e for Europe and the United States, respectively [16]. The costs of CO2-e savings as a result of adoption of Patsari stoves are approximately ~US$3 per tCO2-e given 34 tCO2-e savings for 39% fNRB in the Meseta Purepecha, nominal installation costs of US$100 for a Patsari, and 7-year time horizons for residential small scale household energy projects adopted by the CDM. Not all improved stoves are adopted, however, as the transition to a new technology is moderated by practical and social factors [18]. In addition verification that carbon reductions have been achieved also incurs additional cost. Although these costs are much more variable on a project by project basis depending on stove promotion efforts and monitoring and verification strategies, incorporating a conservative minimum adoption rate of 60% within a community, and monitoring costs from the Patsari project in the Meseta Purepecha, increased costs to US$7 per tCO2-e saving. Even if these costs were 3 times higher, they would still be considerably less expensive than the lower range of costs of carbon abatement technologies in Europe and the United States.

Comparing commonly cited GHG abatement technologies in industrialized nations by England's Department for Business Enterprise and Regulatory Reform indicate nuclear and wind energy in England would be 11 and 17 times more expensive than the Patsari's ~US$7 per CO2-e abated, respectively [19]. Estimates by Sims et al. (2003) indicate CO2-capture from coal plants and solar power in the United States would be 5 and 21 times more expensive than Patsari dissemination [20]. Should stripping CO2 from the atmosphere be required, at current cost of US$140-250 per tCO2 removed [21], cost would be 20-36 fold more expensive than reducingCO2-e emissions to the atmosphere with improved stoves, not including the reduced costs associated with the substantial health improvements of local communities. The substantial health co-benefits in addition to the low relative cost of CO2-e abatement using improved stoves provides a strong rationale for targeting these less expensive carbon mitigation options while alternative low carbon emissions technologies are developed.

Sale of CO2-e savings from improved stoves has the potential to significantly improve stove dissemination efforts in low-income rural communities through defrayment of stove dissemination costs. Carbon prices were ~US$30 per tCO2-e for European Union allowances (EUA) and ~US$5-40 per tCO2-e for voluntary offset programs [22,23]. Assuming a relatively conservative $7 to $15 per tCO2-e within this range, the 34 tCO2-e saving over 7 years with the Patsari's would translate to approximately US$ 250-$500, considerably more than initial stove cost even when adjusting for minimum adoption rates and emissions monitoring expenses. While stove initial costs are only a fraction of total project costs, these monetary benefits illustrate the potential of carbon offset projects to boost improved cookstove projects.

Finally, the increased value of CO2-e savings for communities with a higher fraction of non-renewably harvested fuelwood would tend to focus offset projects in communities with greater resource constraints and environmental impacts, which may also favor improved stove adoption due to perceptions of fuel availability or cost.

Implications and recommendations

Here we demonstrate methods to achieve robust estimates of CO2-e savings from small-scale residential biomass cookstove projects at reasonable cost using an integrated approach of community based sub sampling homes to estimate fuel consumption and emissions, combined with spatially explicit community based estimates of fNRB harvesting. Since emission factors, fuel consumption and fNRB each contribute significantly to the overall uncertainty in estimates of CO2-e savings, community based assessment of all of these parameters is critical for robust estimates. Compared to current carbon mitigation technologies in industrialized nations the low relative cost of CO2-e abatement of improved stoves combined with substantial health co-benefits through reduction in indoor air pollution provides a strong rationale for targeting these less expensive carbon mitigation options for carbon offset trading, especially for those sectors and technologies with relatively inelastic carbon emissions, while providing substantial economic assistance for stove dissemination efforts. Reporting of the overall uncertainty in the CO2-e savings estimates provides a mechanism for valuation of carbon offsets, whereby organizations are rewarded for more time and energy committed to monitoring and verification, without excluding those where such information gathering is limited, but may provide valuable areas for carbon reduction. From a climate perspective this would promote better accounting that CO2-e savings had actually been achieved.

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Table 1: Emissions factors, fuel consumption and fNRB harvesting for community-based sub-samples in the Meseta Purepecha.

Component	N	mean		SD		SE (% of mean)	
		Full	Kyoto	Full	Kyoto	Full	Kyoto
Emission factors (tCO2-e t-1)							
Open fire non-renewable	8	2.24	1.94	0.19	0.19	3	3
Open fire renewable	8	0.54	0.39	0.18	0.19	12	17
Patsari non-renewable*	13	1.93	1.76	0.12	0.08	2	1
Patsari renewable*	13	0.26	0.18	0.11	0.09	12	14
LPG†	8	0.16	3.81	0.16	0.05	<1	<1
Fuel consumption (t yr-1)	N	mean		SD		SE (% of mean)	
Open fire (exclusive)	23	6.21		1.46		5	
Open fire (mixed)	20	4.20		2.01		11	
Patsari (exclusive)	8	1.82		0.66		13	
Patsari (mixed)	6	1.33		0.50		15	
LPG (open fire home)	20	0.16		0.16		22	
LPG (Patsari home)	6	0.06		0.06		30	
fNRB (%)	na	39#		36		14	

* Patsari mean emission factors and standard deviations are pooled from mud-cement and brick stove estimates (Johnson et al. 2007).

† Sample size, mean, and standard deviation are based on measurements performed by Smith et al. (2000).

fNRB in each of 25 individual communities was weighted by the numbers of improved stoves in each community to estimate CO2-e savings.

Table 2. Use of CO2/(CO2+CO) ratio, and char kg-1 to predict CO2-e emissions for the full GHG set (CO2, CH4, CO, TNMHC) and the Kyoto set (CO2, CH4).

Dependent Variable	Adjusted R2		Predictors	B		Std. Error		Std. β		Sig.	
	Full	Kyoto		Full	Kyoto	Full	Kyoto	Full	Kyoto	Full	Kyoto
Open fire CO2-equivalent kg-1 (non-renewable)	0.90	0.78	Constant	2943	2093	528	603	-	-	<0.001	0.006
			Char kg-1	1.0	-0.8	0.3	0.3	-0.50	-0.53	0.002	0.014
			CO2/(CO2+CO)	-2510	-1626	567	648	-0.54	-0.45	<0.001	0.029
Patsari CO2-equivalent kg-1 (non-renewable)	0.94	0.89	Constant	2190	1041	88	75	-	-	<0.001	<0.001
			Char kg-1	-0.9	-0.9	0.1	0.1	-0.57	-0.99	<0.001	<0.001
			CO2/(CO2+CO)	-1783	-607	92	78	-1.02	-0.57	<0.001	<0.001
Open fire CO2-equivalent kg-1 (renewable)	0.79	0.65	Constant	4383	2025	591	413	-	-	<0.001	<0.001
			CO2/(CO2+CO)	-4102	2049	619	433	-0.89	-0.81	<0.001	<0.001
Patsari CO2-equivalent kg-1 (renewable)	0.95	0.90	Constant	1757	1149	90	74	-	-	<0.001	<0.001
			CO2/(CO2+CO)	-1804	-1174	93	79	-0.94	-0.95	<0.001	<0.001

Table 3. Reductions in uncertainty of CO2-e savings by increasing numbers of homes monitored in community based sub samples, assuming the full GHG set and 39% fNRB.

Community based sub samples	Community based sub samples			Feasible sample size		
	N	SE (% of mean)	Contribution to carbon savings CI (%)	N	SE (% of mean)	Contribution to carbon savings CI (%)
Emission factors (tCO2-e t-1)						
Open fire non-renewable	8	3	5	25	2	2
Patsari non-renewable	13	2	<1	25	1	<1
Open fire renewable	8	12	24	25	7	11
Patsari renewable	13	12	1	25	9	<1
Fuel consumption (t yr-1)						
Open fire (exclusive)	23	5	18	25	4	22
Open fire (mixed)	20	11	4	25	9	4
Patsari (exclusive)	8	13	1	25	7	<1
Patsari (mixed)	6	15	<1	25	7	<1
Carbon savings 95% CI	22%			18%		

Figure 1: CO2-e savings and 95% confidence intervals for a shift from open fire to Patsari stoves using a) the full GHG set (CO2, CO, CH4, and TNMHC) and b) the Kyoto set (CO2 and CH4).

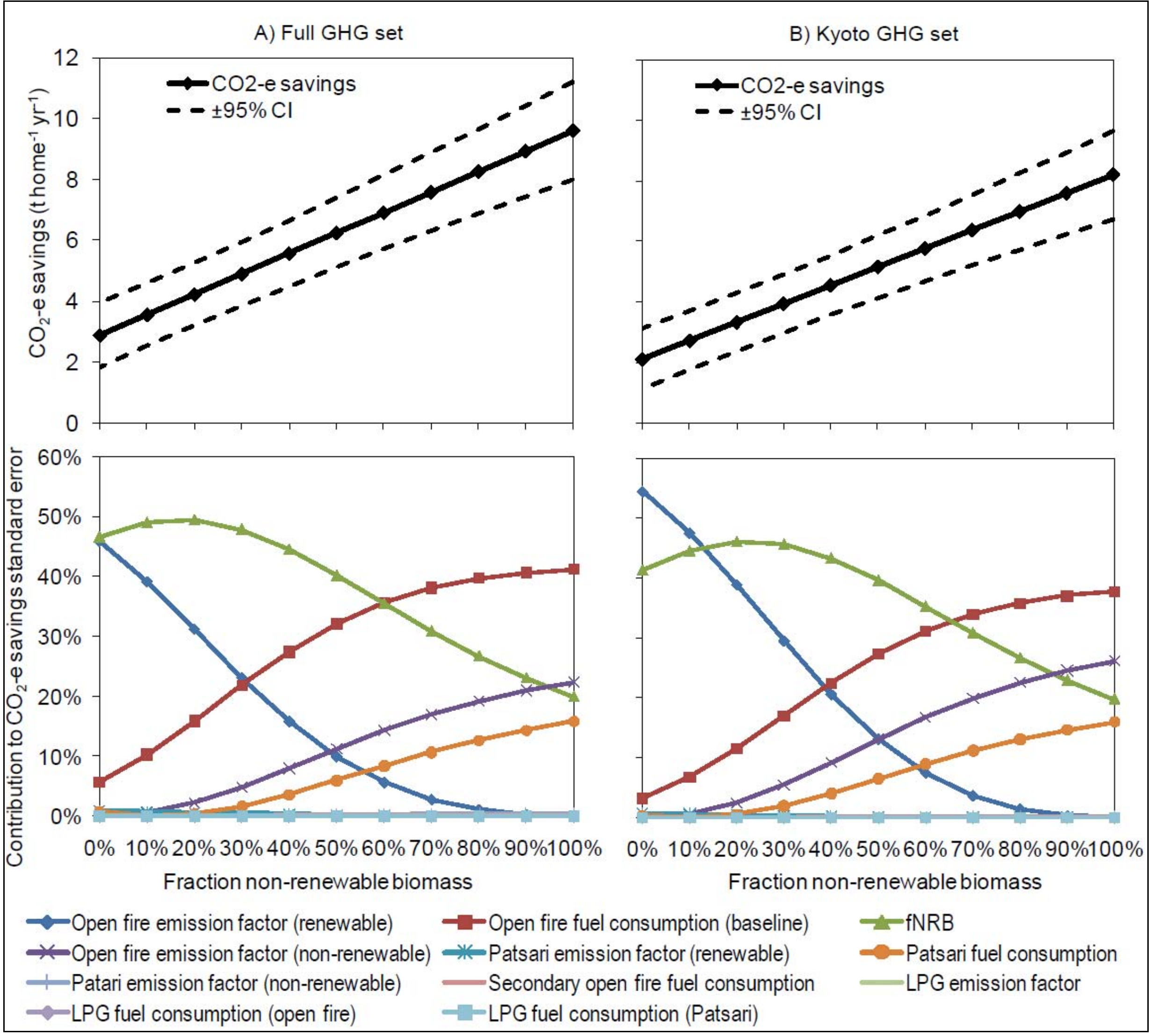
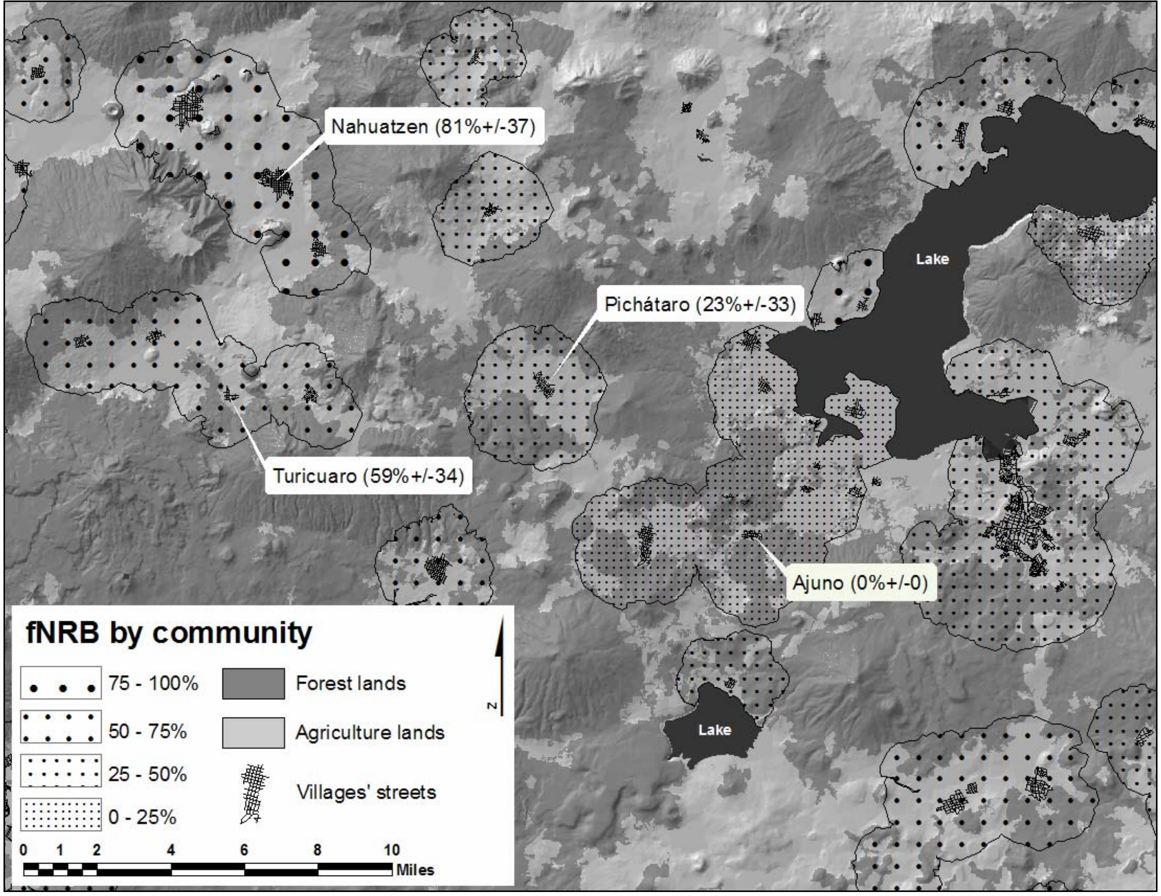


Figure 2. Estimation of non-renewable harvesting of woodfuel on a community basis in the Meseta Purépecha showing the large heterogeneity of harvesting between communities within relatively small spatial areas.



Notes: errors correspond to standard deviations.

Figure 3. Correlation between CO2/(CO2+CO) ratios using a constant flow sampling hood and using a probe suspended above the fire.

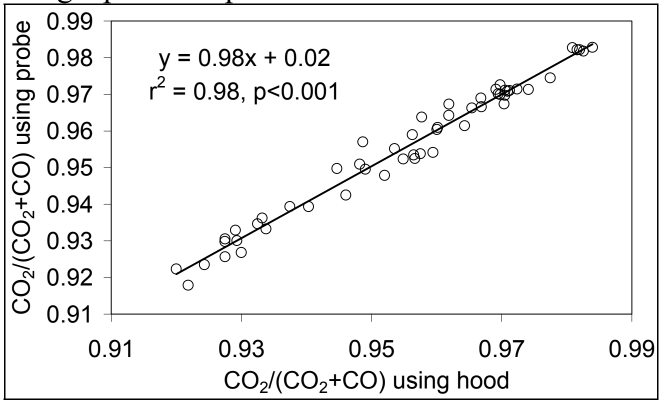


Figure 4. CO2/(CO2+CO) ratio as a predictor for NCE as measured by gas chromatography.

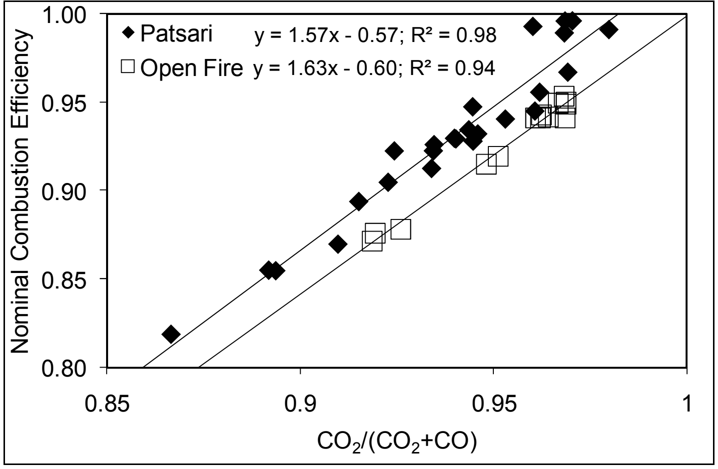
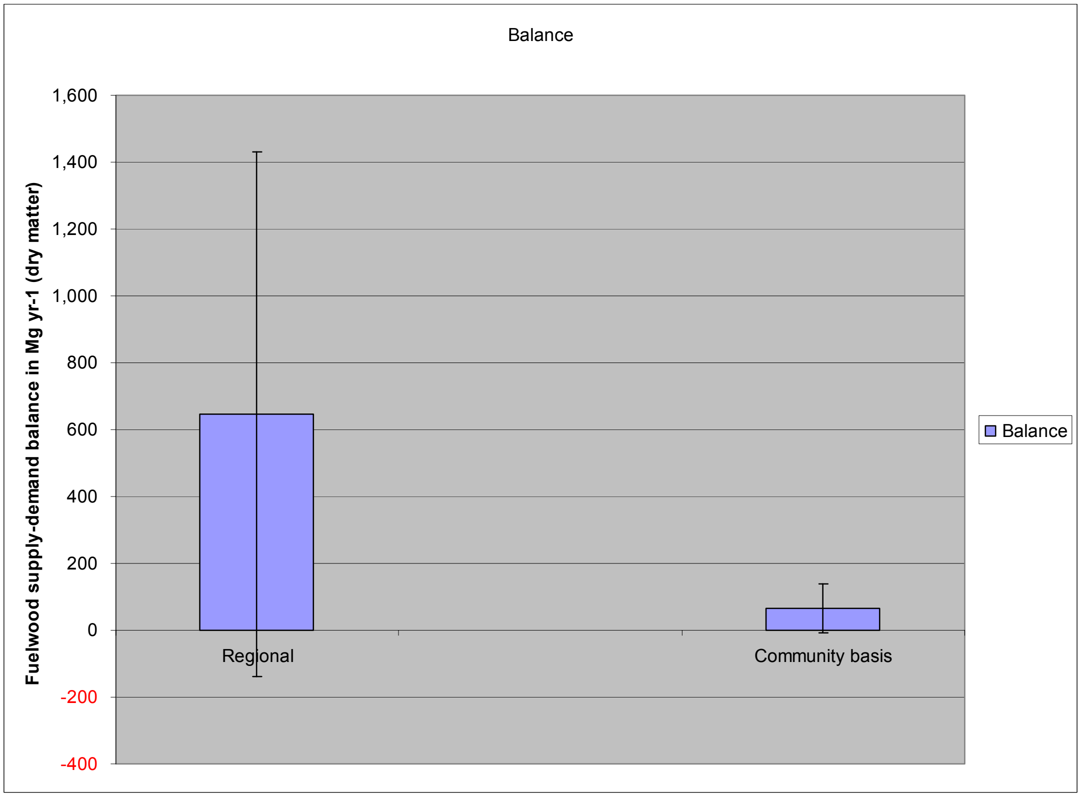
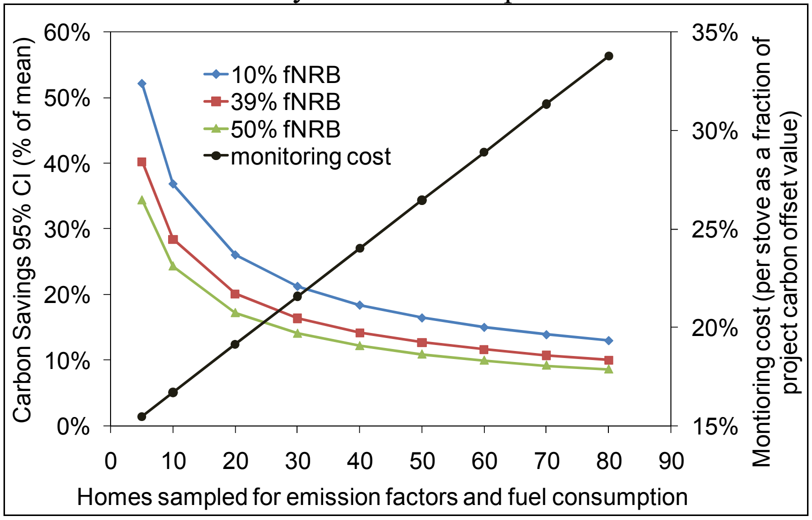


Figure 5: Difference between region wide macro approaches and community level estimates of fuelwood supply and demand compared for communities of the Meseta Purépecha. Refer to Ghilardi et al. (2007 and 2008) for a detailed explanation of the procedure used to get both estimates.



Notes: Adapted from Ghilardi et al. (2008). 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 Meseta Purépecha.

Figure 6. Increased confidence in CO2-e savings in relation to costs of monitoring larger numbers of homes in community based sub-samples.



Notes: Monitoring costs were estimated by assuming a fixed cost of $35,000 plus $600 per home based on our field campaigns in Mexico. Project offset value was determined using 600 adopted stoves saving 3.9 tCO2-e yr-1 for 7 years at a carbon price of $15 per tCO2-e.

ANEXO VI: Fotografías

Recolección de madera muerta por mujeres y niños en la localidad de Ajuno, Michoacán. Notar la diferencia en el tamaño promedio de las varas, comparado con las fotos de la página siguiente donde se utiliza el hacha y un burro como animal de carga. Fotos: A. Ghilardi.

Extracción de leña por hombres en la localidad de Ajuno, Michoacán. El procedimiento consiste en elegir un árbol de alguna especie preferida (un encino en este caso), tumbarlo con el hacha (A), trozarlo *in situ* (B) y transportar los trozos en el animal de carga hasta el hogar (C). La extracción y transporte de leña puede ser una actividad que requiere de al menos 2 o 3 horas, por lo que se suele combinar con otras actividades diarias, como la visita a la parcela. Fotos: A. Ghilardi.

Recolecta de Jara (*Baccharis sp.*) en un área agrícola abandonada en la localidad de Ajuno, Michoacán. La Jara no produce una leña de buena calidad como los encinos y es además un arbusto por lo que sus tallos rara vez superan los 7-10 cm de diámetro. Sin embargo, es una especie muy usada como leña en zonas templadas dada su abundancia (coloniza rápidamente las áreas agrícolas abandonadas deteniendo la sucesión natural hacia bosques de coníferas y latifoliadas) y porque es un subproducto de la limpieza de áreas agrícolas abandonadas. Fotos: A. Ghilardi.

Recolección de leña utilizando un vehículo de carga a motor al costado de una carretera en los altos de Chiapas. La extracción de leña utilizando vehículos de carga a motor no puede realizarse lejos de los caminos. Esta característica, entre otras, permite identificar y categorizar los sitios potenciales de extracción de leña para venta local desde un Sistema de Información Geográfico (SIG). La foto A fue tomada sin previa autorización de los leñadores, que se sintieron de inmediato intimidados, muy probablemente debido que la recolección de leña para su venta local no es una actividad permitida. Fotos: A. Ghilardi.

Oferta de leña proveniente de desechos de la construcción. Foto: A. Ghilardi.

Uso de desechos de la construcción para alimentar un fogón casual en las calles de la ciudad de Uruapan.
Foto: A. Ghilardi.

Notas: A) Uso de gas LP para calentar una olla con carne de puerco con motivo de un evento social en San pedro Tlatizapan, Estado de México. La localidad se ubica al interior del área crítica por uso de leña Nº15 del capítulo III, sección III.2 (Fig.5). B) Uso de leña para elevar la temperatura y completar la cocción durante las últimas 2 ó 3 horas. Se utiliza primero el gas LP para ahorrar leña, dado que es escasa y cara. La leña es la única fuente de energía disponible con la que se consigue la cocción deseada, dado el volumen de la olla, la cantidad de carne en su interior y los dispositivos de uso final: calentador comercial a gas LP y fogón de tres piedras. Es éste un ejemplo de como la leña puede ser un combustible irremplazable bajo ciertas condiciones. Fotos: A. Ghilardi.

A) Venta de leña en la ciudad de Morelia, en vísperas de Navidad. El consumo se leña se dispara durante las fiestas decembrinas, por lo que representa un buen momento para recopilar información sobre los sitios de extracción para el abastecimiento de leña en la ciudad. B) Transporte de leña hacia la ciudad de Pátzcuaro desde algún lugar de extracción incierto. Dado el estado del vehículo y su velocidad (35 km/h), se estima que la leña provenía de bosques aledaños a la ciudad. Fotos: A. Ghilardi.

Uso de leña en Nueva Italia, Michoacán, para preparar una comida cotidiana. Notar el tanque de gas LP, lo que evidencia el uso mixto. Fotos: A. Ghilardi.

Paraderos gastronómicos en la carretera México-Puebla que utilizan leña para la cocción de la mayor parte de los alimentos que venden. Foto: A. Ghilardi.

Sin comentarios. Fotos: G. Morales y A. Ghilardi.