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An assessment of biofuel use and burning of agricultural waste in the developing world

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We present an assessment of biofuel use and agricultural field burning in the developing world. We used information from government statistics, energy assessments from the World Bank, and many technical reports, as well as from discussions with experts in agronomy, forestry, and agroindustries. We estimate that 2060 Tg biomass fuel was used in the developing world in 1985; of this 66% was burned in Asia, and 21% and 13% in Africa and Latin America, respectively. Agricultural waste supplies about 33% of total biofuel use, providing 39%, 29%, and 13% of biofuel use in Asia, Latin America, and Africa, and 41% and 51% of the biofuel use in India and China. We find that 400 Tg of crop residues are burned in the fields, with the fraction of available residue burned in 1985 ranging from 1% in China, 16 - 30% in the Middle East and India, to about 70% in Indonesia; in Africa about 1% residue is burned in the fields of the northern drylands, but up to 50% in the humid tropics. We distributed this biomass burning on a spatial grid with resolution of 1° x 1°, and applied emission factors to the amount of dry matter burned to give maps of trace gas emissions in the developing world. The emissions of CO from biofuel use in the developing world, 156 Tg, are about 50% of the estimated global CO emissions from fossil fuel use and industry. The emission of 0.9Pg C (as CO_2) from burning of biofuels and field residues together is small, but non-negligible when compared with the emissions of CO_2 from fossil fuel use and industry, 5.3 Pg C. The biomass burning source of 10 Tg/yr for CH_4 and 2.2 Tg N/ yr of NO_x are relatively small when compared with total CH_4 and NO_x sources; this source of NO_x may be important on a regional basis.

1. Introduction.

Biomass burning has a significant impact on global atmospheric chemistry since it provides large sources of carbon monoxide, nitrogen oxides, and hydrocarbons, primarily in the tropics [*Crutzen et al.*, 1979, *Logan et al.*, 1981]. These gases are precursors of tropospheric ozone and influence the chemistry of the OH radical [*Logan et al.*, 1981; *Logan*, 1985]. Two notable components of biomass burning are the incineration of wood, charcoal and agricultural waste as household fuel, and the combustion of crop residue in open fields. As the developing world population continues to rise, the contributions from these types of biomass burning increase [*Woods and Hall*, 1994: hereafter referenced as WH94]. A quantitative description of the spatial distribution of biofuel and open field burning is required in order to assess the impact of this burning on the budgets of trace gases.

Earlier estimates of global biomass burning were formulated using simple quantitative descriptions and generalizations. The burning of woodfuel was tied directly to forestry statistics published by the Food and Agriculture Organization (FAO) of the United Nations, while burning of agricultural residues in the developing and developed world was estimated as a fraction of the available residues [e.g., *Seiler and Crutzen*, 1980; *Crutzen and Andreae*, 1990; *Andreae*, 1991; *Hao and Liu*, 1994]. Since many factors such as geoclimatic conditions, vegetation distribution, farming methods, and population densities influence these types of biomass burning, simple global characterizations of these burning practices cannot provide reliable estimates. The purpose of this paper is to provide global distributions that reflect major regional differences in biomass burning. We derive more realistic representations of biofuel and open field burning in the developing countries based on examination of the diverse burning practices found in the tropics. A brief overview of these practices in the developed world is also included. All estimates are based on information pertinent to the specific year of 1985, the year of the GEIA inventories for NO_x and SO2 [*Benkovitz et al.*, 1996]. We also provide estimates for 1995 based on an extrapolation of our inventory for 1985.

We begin with a review of previous global estimates of biofuel and open field burning (Section 2). We follow with a general discussion of biofuel use in developing countries, including specific descriptions of fuelwood, charcoal, and crop residue biofuels (Section 3). The methodology used in this study is described in Section 4. More detailed information on biomass burning in each of Africa, Asia, and Latin America is contained in Sections 5, 6, and 7. We discuss use of biofuels in the developed world briefly in Section 8 and assess potential errors in our estimates for biofuel use in Section 9. We present our results for 1985 in the form of global maps in Section 10, and summarize our findings and compare them with the results of other similar work in Section 11. In Section 12 we give estimates for biofuels use and residue burning for the year 1995. We include estimates of quantities of trace gases emitted from biomass burning in Section 13. Section 14 contains a brief discussion and conclusions.

2. Summary of Previous Work.

Earlier studies [*Seiler and Crutzen*, 1980; *Crutzen and Andreae*, 1990; *Andreae*, 1991; *Hao and Liu*, 1994] used similar methods to calculate fuelwood use in the developing world, basing their estimates in some measure on the assumption that the production of fuelwood as given in the FAO Forest Products Yearbooks is equal to the fuelwood consumption, with modifications using additional data from surveys and estimates of per capita use. Their estimates vary from 620 to 1260 Tg dry matter for the developing world (Table 1). Andreae calculates his estimate as the mean of the FAO fuelwood production and a mean estimate of per capita usage throughout the tropics of 1.3 kg/cap/day. He suggests that using only FAO fuelwood statistics is likely to give low estimates since FAO considers only the marketed fuelwood production. A nonnegligible portion of the fuelwood supply in the developing world is the wood debris which the rural populations gather for household fuel use [*Openshaw*, 1978] and which is not included in the FAO Yearbook estimates.

Most previous studies provide a combined estimate for agricultural residues that are burnt as fuel and those that are burnt in the open fields to dispose of the stubble and to return nutrients to the soil. *Seiler and Crutzen* [1980] and *Andreae* [1991] proposed that 80% of available residues are burned in developing countries and 50% in developed countries. *Crutzen and Andreae* [1990] suggested that 25% of crop waste is burned in the fields of developing countries in the tropics, while *Hao and Liu* [1994] assumed that 23% of residues are used as fuel and 17% are burned in the field.

The work of Hall and colleagues [*WH94*] has been seminal in shifting the focus of study of biomass combustion in the developing world from the use of woodfuels to a more comprehensive picture of 'biofuels' combustion including the burning of crop residues and dung as fuels. Their estimates of biofuel use are based on the FAO fuelwood and charcoal estimates, the Biomass Users Network country studies, data from the U.N. Statistical Office, and, for countries which have little information available, on the following assumption: use of 2.74 kg/cap/day for rural populations and 1.37 kg/cap/day for urban populations [*WH94*]. Unfortunately, their study does not provide a breakdown by fuel type, nor is this breakdown easily determined [D. Hall, personal commmunication, May 1994]. By converting the other estimates to energy units we find that the *WH94* figure of 49.9 EJ biofuels combustion for the sum of developed and developing world is almost one quarter again as large as the high end figure in the range of estimates of biofuel burning of *Crutzen and Andreae* [1990] (19.7-39.3 EJ) .

3. Biofuels.

Rural areas of developing countries depend primarily on biomass for fuel [*Smil*, 1979; *Cecelski et al.*, 1979; *Meyers and Leach*, 1989; *Leach and Gowen*, 1987]. Biofuels include the woodfuels (fuelwood-- see Openshaw [1986] and charcoal), and agricultural waste, such as crop residues and dung. The amount of biofuel consumed varies as climate (higher consumption for colder climates) [*Leach*, 1988], and with the plenitude of fuel resource; where fuel is easily obtained, more is consumed [*Meyers and Leach*, 1989]. The choice of biofuel consumed depends on availability, local customs, and season [*Meyers and Leach*, 1989]. Generally, the sub-Saharan African population depends mainly on wood [*Cecelski et al.*, 1979; *Scurlock and Hall*, 1990], as does the rural population in Latin America. The population in Asia uses all biofuels [*Cecelski et al.*, 1979, *Meyers and Leach*, 1989]. Biofuels are also major energy sources in the urban areas of the developing countries [*Barnes et al.*, 2000]. In the developed world biofuels are important [*Hall*, 1991], but provide a smaller fraction of total energy consumed [*WH94*, *Blandon*, 1983].

3.1. Woodfuels.

Woodfuel is the principal source of domestic energy in developing countries [*Openshaw*, 1974, *Eckholm*, 1975, *Arnold and Jongma*, 1978, *deMontalembert and Clement*, 1983]. Woodfuel includes charcoal as well as firewood, brushwood, twigs, branches, and cut branches [*Openshaw*, 1986]. Where available, fuelwood is generally the biofuel of choice [*Arnold and Jongma*, 1978, *Openshaw*, 1986]. Climate and terrain are the two strongest natural influences on the growth and abundance of the forest resources, and these vary significantly throughout the developing world [*deMontalembert and Clement*, 1983]. Even in countries with adequate fuelwood supply, the resource may be located far from the more populated regions where it is needed [*deMontalembert and Clement*, 1983]. Alternative biofuels are used in regions lacking adequate fuelwood [*Smil*, 1979]. In countries where modern fuels are available and the rural population has the income to purchase them, fuelwood use is correspondingly lower [*Cecelski et al.*, 1979]. The problems of fuelwood supply and conversion in the humid tropics [*Moss and Morgan*, 1981] and in Latin America [*Bogach*, 1985], and projected fuelwood deficit throughout the world [*Wood and Baldwin*, 1985] have been discussed also in earlier works [*Earl*, 1975, *Openshaw*, 1986].

3.1.1. Charcoal. A large fraction of urban populations in the developing countries relies on charcoal for cooking and industrial fuel [*Barnes et al.*, 2000]. We consider charcoal as a separate fuel since trace gases are emitted during its production [WH94], and emissions from burning charcoal differ from those for wood. The carbonization process used in converting wood to charcoal is generally inefficient, and volatiles including CO_2, CO, CH_4, and non-methane hydrocarbons (NMHC) estimated at 60% by weight of the original wood are emitted [*WH94*]. *Openshaw* [1978, 1980, 1986] suggests that from six to twelve tons of wood are required to make one ton of charcoal.

Nearly all of charcoal production occurs in the developing world [*Lew and Kammen*, 1994]. About half of the world's charcoal is produced in Africa where it is used as a domestic fuel in many of the urban areas and as a cooking fuel in eastern and northern regions [*Foley*, 1986, *Hibajene et al*, 1993]. In Asia, the pattern of charcoal consumption varies from extensive use as a domestic fuel in both urban and rural Thailand [*Foley*, 1986, *Ishiguro and Akiyama*, 1995], and as a large industrial fuel for the steel industries in the Philippines and Malaysia [*Foley*, 1986], to a much smaller role in the domestic energy supply in India [*Foley*, 1986, *Leach*, 1987]. In Latin America charcoal is not a major household fuel, but is a notable source of energy for the steel industries of Brazil [*Bogach*, 1985, *WH94*], Bolivia, [*World Bank (WB): Bolivia*, 1994], and Paraguay [*WB: Paraguay*, 1984]. A detailed overview of charcoal consumption in the developing countries is given in Wood and Baldwin [*1985*].

3.2. Agricultural Residues.

Billions of tons of agricultural waste are generated each year in the developing and developed countries. Agricultural residue includes all leaves, straw and husks left in the field after harvest, hulls and shells removed during processing of crop at the mills, as well as animal dung. The types of crop residue which play a significant role as biomass fuels are relatively few.

The single largest category of crops is cereals, with global production of 1800 Tg in 1985 [*FAO*, 1986a]. Wheat, rice, maize, barley, and millet and sorghum account for 28%, 25%, 27%, 10%, and 6%, respectively, of these crops. The waste products which are the main contributors to biomass burning are wheat residue, rice straw and hulls, barley residue, maize stalks and leaves, and millet and sorghum stalks. Sugar cane (0.95 gigatons) provides the next sizeable residue with two major crop wastes: barbojo, or the leaves and stalk, and bagasse, the crop processing residue. The cotton crop also gives nonnegligible residue in the form of stalks and husks, both of which are used as biofuels. Four minor crops provide residue from processing that is frequently used as fuel: palm empty fruit bunch and palm fiber, palm shells, coconut residue, groundnut shells, and coffee residue.

Geographical distribution of crop residue (Table 2) is skewed by large crop productions in India and China [*FAO*, 1986a]. The other countries of southeast Asia have rice and sugar cane as dominant crops. In the Middle East, the crop mixture is more diverse with more cereals and less rice and sugar cane. In the drylands of the Near East and Mediterranean northern Africa, wheat and barley predominate. In the sub-Saharan Sahel in Africa, millet and sorghum are the main crops (Table 2). Farther south in the subhumid and humid regions, maize is important. All three grains are grown in the highlands of eastern Africa. In Latin America, the crop residues of maize and sugar cane provide significant field and factory waste, with Brazil as the foremost contributor.

Crop residue accumulates in the fields and in factories. The waste from the agroprocessing industries accumulates at the mills where the crop is prepared for consumption. These include bagasse residue from sugar cane [*WB: Ethiopia*, 1986], rice husks, cottonseed hulls, palm, coconut, ground nut, cashew, and coffee processing waste. Agroindustrial biomass waste is used mainly as fuel for the processing industry, and is rarely transported any distance from the mills for other purposes [*Barnard and Kristoferson*, 1985, *Openshaw*, 1986]. It is generally unpalatable as fodder, and inaccessible, except locally, for household fuel. A more comprehensive discussion of these agroindustrial wastes and estimates of use as fuel is included in Appendix 1.

In the developing world the grain residues are used in various ways: household fuels and construction materials in wood-deficit regions, and livestock fodder in dryland regions, as described in Sections 5, 6, and 7. The major field residues are sugar cane barbojo, and post-harvest grain residues as well as cotton stalks. Traditionally, the barbojo is burned in the fields as a pre-harvest measure to facilitate the harvesting of the sugar cane [*Williams and Larson*, 1993]. Cotton is a "woody" plant [*Townsend*, pc], a more likely substitute for fuelwood as household fuel, and a less likely fodder source. In addition, cotton is susceptible to a large number of pests and plagues [*Percy*, pc], so the cotton plants are destroyed after harvest to curtail the spread of pest and disease [*WB: Burkina*, 1986, *WB: Ethiopia*, 1984, *Ramalho*, pc, *Valderrama*, pc, *Tothill*, 1954, *Matthews*, pc]. The cotton stalks are either: mechanically destroyed and the leftover ploughed down [*Hadar et al.*, 1993], as in many Latin American countries where tractors are more accessible [*Ramalho*, pc, *Valderrama*, pc, *Cuadrado*. pc, *Jones*, pc]; burned in heaps as in Africa where tractors are scarce [*Tothill*, 1954, *Matthews*, pc, *Gray*, pc, *Poulain*, 1980, *Carr*, pc]; or burned as fuel, as in several Asian countries where fuelwood substitutes are needed [*Chaudry*, pc, *Townsend*, pc].

4. General Methodology.

Detailed information on local fuel consumption and local burning practices is required to construct a credible assessment of biofuel consumption and open field burning in the developing world. This information is usually gathered in survey/questionnaire form. Reliable surveys are difficult to obtain: short term surveys frequently cannot account for seasonal fluctuations in residue fuel availability [*Hall and Mao*, 1994]; surveys which describe rural village habits in one locale may not be adequate to describe the habits of rural communities located in different geoclimatic regions within the same country [*Hosier*, 1985]; surveys may not document factors which affect biofuel consumption such as fuelwood moisture content [*Openshaw*, 1986]. Difficulties in survey practice are discussed in detail in *Hosier* [1985] and *Kgathi and Zhou* [1995], while *Openshaw* [1986] provides guidelines for constructing comprehensive surveys of biofuel use.

4.1. Sources.

Energy assessments for individual countries conducted by the World Bank (WB) and the United Nations Development Programme (UNDP) provided the main source material used in this analysis. These reports give information on the available energy supplies, with data obtained from government sources and/or from surveys conducted by participants involved in the country study. They usually include an annual energy balance which contains estimates for use of fuelwood, charcoal, bagasse, and other agricultural residues as fuel. The quality of information varies, depending on the accuracy of the government sources, and the nature of the surveys [*Openshaw*, personal communication; *Openshaw*, 1986].

The second major group of sources comprises individual reports for countries or regions. The information in these reports ranges from direct quotations of governmental energy statistics on biofuel use to descriptions of very careful surveys which included many participants, extended through several seasons and several locations to provide a comprehensive database for analysis. Several of the more detailed reports will be described in Sections 5, 6, and 7.

Agricultural statistics usually published as government documents give details on quantities of crops and livestock distributed within the provinces or states of a particular country. These were included in the literature survey, as well as statistics on estimated forest land and pasture/grazing lands. Various treatises on biological processes were consulted to ascertain modes of biomass decomposition in differing climatic conditions. Other botanical papers were examined to determine more information about crop growing, processing and consumption practices in the developing world. Specific information on crop residue use was frequently included.

Finally, discussions with personnel in the sugar and cotton processing industry, agronomists, botanists, and foresters, and others with experience in the developing world yielded a plethora of anecdotal evidence providing personal observation on burning practices indicative of large-scale burning activities within some developing countries.

4.2. Procedure.

Biofuels

Estimates of biofuels consumption are presented for different survey years in diverse energy, volumetric, and gravimetric units, sometimes disaggregated into individual types of biofuel use, sometimes reported as a total biofuel consumption. (We discuss the conversion factors used in this paper in Appendix 2.) Most results were reported in mass or volume units; where these were the main sources (e.g. for Africa), we derived rates of fuel consumption per capita. We assumed that household fuel consumption correlates with population size, and computed total biofuel use for a given country by multiplying the per capita usage by the population for that country for 1985 (*Demographic Yearbook*, 1992). In contrast, most sources for Latin

America provided biofuel use in energy units. We utilized this information directly in presenting the complete biofuel scene for Latin America in energy units in Section 7. We include a discussion of energy content of various biofuels in Appendix 2. In tables which compare biofuels use in Latin America and other developing continents, all estimates are expressed in terms of teragrams (Tg) of dry matter fuel consumed.

4.2.1 Woodfuels

Woodfuels consumption statistics were separated into fuelwood use, consumption of wood to make charcoal, and charcoal consumption. Charcoal use in Africa is primarily an urban phenomenon; we therefore present charcoal use in units of weight-per-urban-capita.

Data on charcoal use is available either as the total amount charcoal consumed or as the total amount of wood used to produce the charcoal. For both Africa and Asia we estimate charcoal consumption in units of wood used to produce charcoal, a figure calculated from the amount of charcoal used by assuming an efficiency of charcoal production, the fraction by weight of the wood that ends up as charcoal. All efficiencies in this paper are given as percent by weight. The maximum efficiency in converting wood to charcoal is approximately 30%. Most charcoal production is more inefficient than this [*Openshaw*, 1986], with the major exception of the industrialized production in Brazil [*WH94*]. Efficiencies adopted in this study are given in Appendix 3.

4.2.2 Residues as Biofuels

For estimating agricultural waste used as biofuel, a many-faceted approach was taken. We converted any reported estimates of agricultural waste used as biofuels to units of dry matter per capita. In other circumstances, especially in Africa, when reports specified a woodfuel deficit and the use of agricultural residues as substitute fuel, we estimated the consumption of residues as fuel in sufficient quantity to fill the woodfuel deficit [*Openshaw*, 1986; *Polycarpou and El-Lakany*, 1993; *Pokharel and Chandrashekar*, 1994]. Many reports noted that agricultural residues were not used for fuel, either owing to sufficient woodfuels available, or need of the residue for other purposes. For the dung component of biofuels, we relied on reports of specific use in a country.

4.3 Burning in Fields

The open field burning of agricultural residue is well documented [e.g. *Ponnamperuma*, 1984, *Williams and Larson*, 1993, *Poulain*, 1980]. We used direct estimates of amount burned in the fields, when available. The actual amount of crop residue as dry matter (DM) available for burning was determined from the country-by-country tallies of crops produced in 1985 [*FAO*, 1986a], the residue-to-crop ratios described below, and some estimate of the fraction of residue burned. For example, we prescribed the default fraction of available barbojo residue which burns to be about 85%, since a complete burn is rare [J. Kadyzewski, personal communication]; barbojo is used for construction in some regions (see Section 6). In general, to estimate the percent burned, we referenced discussions with agronomists about the fate of residues of specific crops (cotton, sugar cane, wheat and barley) in different regions of the world, and constructed a plan of open field residue burning for these particular crops. For the remaining residues, we first ascertained whether residues were needed for other purposes, allotted the fraction of residue to each designated use, and assumed the remainder was burned in the fields, if this practice is common in the region. We were often informed that open field burning was never seen in given regions, or that, in contrast, all agricultural waste was burned throughout the countryside.

4.4 Residue-To-Crop Ratios

The amount of residue produced as compared with the amount of crop grown depends on climate and fertilizer use, and on whether the crop is a high-yielding variety [*Barnard and Kristoferson*, 1985]. Many low income farmers in the developing world choose to save seed from the old cultivars which produce a high stalk/crop ratio, rather than purchase the modern cultivar seed more often used in the developed countries [*Bradow*, pc, *Percy*, pc]. We present a summary of residue/crop ratios available from the literature since 1985 in Table 3, which compares these values with the review of *Barnard and Kristofferson* [1985]. We have selected default ratios which we feel best approximate average residue/crop production ratios for each type of residue, acknowledging the variations in crop variety, climate, and differences in farming practice, as shown in Table 3. Country specific ratios were used where substantially different from the default values.

5. Africa.

Africa has the lowest per capita consumption of modern fuels in the developing world [*Davidson*, 1992]. Modern energy resources are concentrated in a few countries such as Nigeria, Libya, and South Africa [*Kahane and Lwakabamba*, 1990]. Most African countries are predominantly rural and economic output is low, so that the population cannot afford to buy oil-based fuels. The rural population (and often the urban population also [*Cecelski et al.*, 1979, *Barnes et al.*, 2000]) relies on wood and charcoal as the main fuels for domestic consumption [*deMontalembert and Clement*, 1983].

5.1 Woodfuels.

Africa is marked by contrasts in geoclimatic and vegetation conditions, from the northern drylands through the large desert and savanna zones with fuelwood deficits, to the forest zones with fuelwood surplus, to the more populous temperate eastern highland areas. Lack of infrastructure makes the transportation of wood from surplus to deficit regions difficult. The per capita woodfuel consumption depends on availability and demand, and ranges from an estimated low of 0.05 kg/cap/day in Lesotho to upwards of 3.0 kg/cap/day in Eastern Highland countries (see Table 4).

5.1.1. Fuelwood. To facilitate analysis of fuelwood availability and consumption, we subdivided the continent into regions (Table 4), grouping together neighboring countries that share similar woody vegetation and population density. Note, however, that an average per capita fuelwood use cannot describe local and regional variations.

The Mediterranean countries of North Africa have more in common climatologically with the rainfed drylands of the Middle East than with sub-Saharan Africa. Fuelwood consumption is negligible in oil-rich states like Libya [*deMontalembert and Clement*, 1983] and modest in countries like Algeria, which, though a large oil-producer, has forested mountain zones and a sizeable low-income rural population (Table 4).

The Sahel countries to the south are sparsely populated with desert and subdesert mixed with savanna regions. Chad, which has desert in the north, and desertification and drought conditions in the south, has the lowest fuelwood consumption of 0.3 kg/cap/day. Mali, with its sufficient-to-surplus wood in western and southern regions [*WB: Mali*, 1991], but major woodfuel shortages in the three northeastern regions (identified using satellite data [*WB: Mali*, 1992]) has the highest consumption of 1.49 kg/day. Sudan is an exception within this group in that its northern climate is desert, while its southern regions have tropical forests and savannas.

The coastal countries of West Africa contain areas of wooded savanna and dense forest, with sparse to heavy population density. The fuelwood consumption estimates are mostly within the range of 1.3-1.7 kg/cap/day. Guinea, which has extensive forest cover and abundant fuelwood resources, is a notable exception, with 3.2 kg/cap/day [*WB: Guinea*, 1986]. The country which dominates fuelwood use in Africa, Nigeria, is included in this group, although its northern provinces are in the Sahel region. Our estimate for Nigeria is based on the Silviconsult, Ltd survey (over 2350 households) of the five northern provinces [*Hyman*, 1994] and the very careful surveys of Kersten et al. [*1998*] in the Osun State of southern Nigeria. Kersten et al. [*1998*] found that even in the rural areas where an adequate supply of wood was available, there was low per capita consumption.

The countries of Central Africa have large zones of dense forest with low population density, and relatively high consumption rates, 1.5-2.5 kg/cap/day. Some countries such as Gabon and Equatorial Guinea are relatively prosperous [*WB: Gabon*, 1988] and their populations use substantial quantities of modern fuels in addition to woodfuels.

The highest fuelwood consumption rates occur in the highland countries of southeastern Africa, at 1.89 to 3.24 kg/cap/day, a consequence of plentiful forest resources and use of fuels for heating. Malawi [*WB: Malawi*, 1982], Uganda [*O'Keefe*, 1990], and Zambia [*WB: Zambia*, 1983] have extensive forest reserves. Kenya has productive forest land in the central highlands [*Senelwa and Hall*, 1993], and Tanzania has about 40% forest cover, much of this miombo woodlands [*Hosier et al.*, 1990; *WB: Tanzania*, 1984].

Countries of the eastern and southern drylands region include sparsely populated savanna areas and dry mountainous zones of degraded forest cover [*deMontalembert and Clement*, 1983]. In many areas crop residues and dung are used as alternate fuels to supplement fuelwood, since fuelwood is scarce. Fuelwood consumption is fairly low, between 0.05 kg/cap/day in Lesotho and 1.84 kg/cap/day in Ethiopia, with an outlier of 2.04 kg/cap/day in Botswana.

Within the island group there is a wide range of fuelwood consumption. The largest population inhabits Madagascar which is densely populated and whose fuelwood resources are being rapidly depleted.

Five countries, Nigeria, Ethiopia, Tanzania, Kenya, and Zaire use 138 Tg/y of fuelwood or about 50% of the total for Africa (Table 4). Usage varies from 1.50 kg/cap/day in Nigeria to 3.21 kg/cap/day in Tanzania. The detailed surveys for Nigeria were discussed above. Ethiopia is classified in the Eastern/Southern Drylands region, but straddles the Eastern Highlands region; the per capita consumption of 1.84 kg/cap/day is somewhat high for the Eastern/Southern Drylands region. For Tanzania, *Hosier et al.* [*1990*] compared the results of four major reports on woodfuel balances, including Kaale [*1983*] on districts facing wood-deficit, Openshaw's [*1984*] analysis based on surveys in the 1970's, a World Bank ESMAP (Energy Sector Management Assistance Programme) [*1984*] assessment of the woodfuel-deficit regions, and Luhanga and Kjellstrom [*1988*] based on remote sensing information. Hosier et al. [*1990*] analyzed the differences in these studies and noted that, while different in detail for the twenty regions of Tanzania, their average estimates were remarkably similar.

Hosier [1985] compared the results of his survey of energy consumption in 1981 taken in rural households in different ecological zones of rural Kenya with the results of a 1978/1979 survey among the same households. He noted that the average consumption rate of fuelwood had decreased from 2.44 kg/cap/day to 2.17 kg/cap/day. More recently, *Kituyi et al.* (1999) conducted extensive surveys in both rural and urban regions of Kenya in early 1997 using Hosier's methods and estimated a rate of 1.75 kg/cap/day. We derived a weighted per-capita firewood use of 1.89 kg/cap/day from the rural estimate of Hosier [*1985*] and the urban estimate of *O'Keefe and Raskin* [1985] along with the work of *Kituyi et al.* [1999].

Detailed analyses are available for some countries that make smaller contributions to fuelwood use in Africa. Country-by-country summaries are included in *O'Keefe and Munslow's* [1984] report on southern Africa and *Karekezi and Mackenzie's* [1993] discussions on energy options. Several studies combine aerial and satellite remote sensing together with concomitant ground surveys to define coherent data pictures of biomass energy supply and demand [*Hall and Mao*, 1994, *WB: Mali*, 1991].

5.1.2. Charcoal. Africa has the largest per capita charcoal use among the developing continents [*Lew and Kammen*, 1994]. Information on charcoal use is provided in Table 5.

The greatest per capita use is in the East African Highlands. These countries have a substantial wood supply which can be converted to charcoal and then transported to regions of demand. By contrast, little charcoal is used in the Southern Drylands. Urban users in Zimbabwe and Swaziland prefer firewood and coal [*Hemstock and Hall*, 1997]. No charcoal is produced in Botswana [*Wisner*, 1984]. In Lesotho [*Frolich*, 1984], Botswana [*Hall and Mao*, 1994], and Namibia [K. Openshaw, personal communication], the urban population uses firewood, kerosene, and coal.

Sudan is unusual in that charcoal is significant as an energy source for both the urban and rural populations [*Digernes*, 1977; *Craig*, 1991]; almost 80% of the charcoal consumed in the Central Region is used by the rural population [*Elgizouli*, 1990]. This explains the very high charcoal use expressed in per urban-capita units in Table 5.

Among the remaining countries, there are no obvious regional preferences. For West Africa, the urban populations of Burkina Faso, Mali [*WB: Mali*, 1991), and Niger prefer using firewood to charcoal, but the populations in the largest cities of Ghana use more charcoal [*Foley*, 1986]. Similarly, surveys indicate that city dwellers in Guinea [*WB: Guinea*, 1986], Togo [*WB: Togo*, 1985], Senegal [*Lazarus et al.*, 1994; *Foley and van Buren*, 1982], and Sierra Leone [*WB: Sierra Leone*, 1987] are heavy charcoal consumers.

5.2. Agricultural Residues.

Crop residue produced in Africa accounts for about 10% of the total agricultural residue in the developing world, as shown in Table 2 [*FAO*, 1986a]. We examine the fate of these residues in the five agro-climatic regions described by *McIntire* [1992], and results are presented in Table 6. About 80% of wheat and barley is grown in the rainfed drylands of the northern coast, while a similar fraction of millet and sorghum is grown in the sub-Saharan semi-arid Zone. Egypt, Madagascar, and Nigeria provide 62% of the rice residues in Africa, and Egypt and Sudan together produce 47% of the cotton residues. Maize is grown for the most part (about 75%) in the eastern countries of Africa, from Egypt south through the temperate highlands countries to, and including, South Africa. Most of the minor agro-industrial crop waste of palm (95%), coffee (56%), groundnut (50%), and coconut (40%) is produced in the tropical subhumid and humid zones.

5.2.1. Rainfed Drylands Zone. The residues of the wheat and barley grown in Mediterranean north Africa are generally used as livestock feed (Figure 1) [*Hadjichristodoulou*, 1994; *Whitman et al.*, 1989], similar to practices in the Near East (section 6.2). In Algeria, barley is grown primarily for fodder [*Tully*, 1989]. In Morocco, the cereal crop residue and barley crops are the main forage for the ruminant livestock [*Tully*, 1989; *Fenster*, 1989]. Once the residue has been harvested for winter feeding, the ruminants are allowed to graze the remaining stubble. We assumed 99% of the residues are used for fodder, and, as there is evidence of burning where livestock are few [*United Nations Environment Programme*, 1977], we arbitrarily assumed that 1% of residues are burned in the field before planting (Figure 1, Table 6).

5.2.2. Semi-Arid SubSaharan Zone. This zone with annual precipitation of 200-1000 mm/yr and frequent drought is a region of low biomass productivity, lacking forest cover. The major crops which can be grown without irrigation are millet, sorghum and cowpea [*Christensen*, 1994; *Norman*, 1981]; maize, groundnut, rice, and cotton are also grown. This region produces the most agricultural residue in Africa, in part because of the high residue to crop ratios from millet and sorghum and maize. As in the drylands zone, crop residues are a good source of feed for livestock, especially in the post harvest and dry seasons [*Tothill*, 1954: *Norman*, 1981; *Lamers et al.*, 1996; *McIntire*, 1992; *Sandford*, 1989]. Crop residues are also needed as household fuel [*Ernst*, 1977]. Sorghum and maize stalks are important construction materials [*Reddy*, 1981; *F. Harris, M. Mortimore*, personal communication]. Whatever crop residue remains after these uses is either decomposed, eaten by termites [*Ofori*, 1989; *Miracle*, 1967], or burned in the open field prior to the planting season [*Watts*, 1987].

Livestock are integral to the lives of the farming and transhumant herder populations. In detailed aerial and ground surveys of land use covering 1.5 x 106 km2 in sub-Saharan Africa, a strong correlation was found between livestock density and the amount of cultivated land [*Wint and Bourn*, 1994]. While many tribesmen are exclusively stock owners, farmers who do not own any livestock are rare [*Pingali et al.*, 1987; *Mortimore*, 1987; *Dederi*, 1990; *Draft Report*, 1986]. The rural population needs crop residues for both fuel and fodder [*Alhassan*, 1990; *Umunna*, 1990; *Morgan*, 1980]. In Burkina Faso [*Sivakumar and Gnoumou*, 1987], Mali [*Dicko and Sangare*, 1986], and Niger [*Reed*, 1992], reports provide evidence of large herds of cattle, sheep, and goats grazing post-harvest crop residues.

While the importance of cereal residues as fodder is evident [*Oyenuga*, 1968], the task of quantifying this use is difficult. We relied primarily on measurements of vegetation grazed in millet and sorghum fields. In Niger, farmers usually leave the residue of the millet crop in the fields for cattle to graze [*Reed*, 1992]. Measurements showed that 100% of the millet leaves and about 30% of the millet stems were eaten by cattle [*McIntire*, 1992]. In neighboring Nigeria, the main use of sorghum straw is for post-harvest and dry season animal feed [*Alhassan*, 1990, *Umunna*, 1990]. Studies on grazing habits indicate that in eight weeks after harvest, cattle graze almost all leaves, 47% of millet stalks and 40% of sorghum stalks [*Powell*, 1985]; another study suggests that passing ruminants graze 34% of the total edible sorghum residue left in the fields [*van Raay and de Leeuw*, 1971]. These data indicate that 30-43% of millet and sorghum residue collectively are grazed by cattle. Given that sizeable numbers of sheep and goats also graze in the semi-arid zone, we selected the upper end of the range, 43%, to represent the amount of millet and sorghum stalks used for fodder.

Straw and stalks in the semi-arid zone are used in construction of fences, houses, and compounds [*Reddy*, 1981; *van Raay*, 1975]. In this case, post-harvest millet and sorghum fields are burned rapidly to clear leaves: the stalks are then cut and bundled for construction use [*WB: Benin*, 1985]. As much as two-thirds of available sorghum stalks are estimated to be used for construction in Kano, Nigeria [*F. Harris*, p.c.]. On farms with no livestock, millet straw is often used as a mulch [*Poulain*, 1980]. We estimate that 20% of residue is used for construction, mulching, low-level decomposition in this dry region, and termite attack.

A significant portion of crop residue in this zone is used for household fuel (Table 6). Figures for the estimated woodfuel deficit in the northern provinces of Benin [*WB: Benin*, 1985], Burkina Faso [*WB: Burkina*, 1986], Mali [*WB: Mali*, 1991], Togo [*WB: Togo*, 1985], and Nigeria [*WB: Nigeria*, 1993, *Draft Report*, 1986, *Population Association*, 1991] together with estimates of the rural population in each province were combined to give a crude guess as to per capita woodfuel deficit. From this, a per capita residue-as-substitute-fuel was estimated, and the corresponding amount of residue needed as fuel calculated. For those countries and regions where surveys of residue biofuel use were reported, these estimates superceded our rough calculations.

To summarize, approximately 60% of the residue was apportioned for non-burning uses, with the remainder either burned as household fuel or as trash in the field. We use country specific reports as guidelines for partitioning the leftover residue between these two types of burning (Table 6). The farmers burn the leftover stubble to release nutrients into the soil in preplanting field preparation in March and April [*Watts*, 1987; *Poulain*, 1980].

5.2.3. Sub-Humid Zone. The subhumid zone covers a band south of the semi-arid region through the center of west Africa and into east and southern Africa. This zone is better suited for agriculture, with 1000-1500 mm/yr rainfall [*McIntire*, 1992] and a growing period of six to nine months. A greater variety of crops is grown here with more maize and rice than in the semi-arid zone. However, this zone is less favorable for livestock, due to prevalence of trypanosomiasis and other livestock diseases [*Areola*, 1991; *Sivakumar*, 1987]. In estimating fodder use of the residues for the livestock, we note that millet and sorghum are grown in roughly equal proportion in this area; using the post-harvest grazing measurements of Powell [*1985*] as a guide, we assume 43% of millet and sorghum residue are used for fodder. We assume that maize residue is used in similar proportions. We note that much of the crop residue decomposes in this zone, given the favorable temperature and moisture conditions (see Appendix 4).

Most countries, with the exceptions of Malawi and Ivory Coast, have sufficient wood for household use, so there is limited need of residues for construction or fuel. We apportion the remaining cereal residue for decomposition (based on the information in Appendix 4), termite consumption, and mulching, with open field burning of any residual crop waste.

The cotton harvest residue is another nonnegligible crop waste. The stalks are usually piled in heaps in the field and burned [*Poulain*, 1980; *WB: Burkina*, 1986], and the cottonseed hulls accumulating at the mills are used mainly as fuel (see Appendix 1).

5.2.4. Humid Zone. This zone which extends along the coast of west and central Africa and through the Congo has heavy rainfall and a long growing season [*McIntire*, 1992]. Many different crops are grown, and here also, livestock numbers are low due to threat of stock diseases [*McIntire*, 1992]. Since forests and natural grazing lands are abundant, crop residue is not in great demand for either fuel or fodder. For the disposition of these residues, we propose the following. After the harvesting and some livestock grazing, the remaining residue decomposes in the fields for four to six months until March or April. The farmers then burn (Figure 1) the leftover crop waste in the fields before planting [*Watts*, 1987; *Miracle*, 1967; *J. Holtzmann*, pc]. Based on the discussion in Appendix 4, we estimate that in the time between grazing and the spring preplant burn, 52% of millet and sorghum straw and stalk, 62% of maize stalks, and 50% rice straw decompose. These estimates are adjusted if country-specific information is available on the fate of the individual crop residue.

5.2.5. Highland Region. The highland region has a temperate climate, good soils, and a long growing season [*McIntire*, 1992]. The cooler climate fosters a higher population density and also higher livestock density, as the threat of trypanosomiasis is almost nil [*McIntire*, 1992]. The high livestock count in the countries in this zone, Kenya, Ethiopia, Tanzania, Rwanda, and Burundi, suggests that much of the edible crop residue is used for animals [*McIntire*, 1992]. In addition to fodder, the residue is needed as household fuel (Table 6, Figure 1).

In Kenya crop residue is a commodity, bought or exchanged for plowing time, grazing land, etc. [*McIntire*, 1992; *English et al.*, 1994]. Although Kenya has one of the highest rates of fuelwood use in Africa, *Senelwa and Hall* [1993] estimate that over 40 PJ (or, about 2.76 million tons) of crop residue (mainly sorghum and maize stalks) is used as household fuel. The use of millet stems as fuel is also reported [*Mburu*, 1989]. To achieve the level of household fuel estimated by Senelwa and Hall, we apportioned the fate of maize residue as 70%:20%:10% for fuel:fodder:decomposition. The sorghum and millet stalks/stems were divided equally between household fuel and decomposition in fields, as millet stems are rarely used to feed animals, but usually gathered for fuel or left to decompose in the fields [*Mburu*, 1989].

In Tanzania the rural areas depend almost exclusively on wood for fuel, despite a number of wood-deficit regions in the country [*Hosier et al*, 1990]. We assigned its millet, sorghum, and maize residues to reflect this, prescribing only 15% for household fuel use. In contrast, there are many fuelwood deficit regions throughout Ethiopia [*WB: Ethiopia*, 1984], so that dung and crop residues are also used as household fuel.

6. Asia.

Asia is the largest contributor to the burning of biofuels and agricultural residue in the developing world, because of the dominance of China and India; these countries are described in Sections 6.3 and 6.4, respectively. Estimates for woodfuel consumption are given in Table 7 and those for residue fuel use and field burning in Table 8. Aside from China and India, eight other countries account for 75% of the remaining biofuel (woodfuel plus residue fuel) consumption on the continent; Indonesia, Vietnam, Thailand, Philippines, Turkey, Myanmar, Bangladesh, and Pakistan. Indonesia is the main contributor, with the largest population in Asia after China and India. (Note that while we list the biofuels use in Japan as part of Asia's total, it is not considered a developing country.)

Throughout Asia, regions of similar geography and climate frequently share similar patterns of biofuels use. In the Near East drylands many countries have abundant supplies of petroleum. However, rural populations of some of the larger of these countries use wood, as well as significant quantities of residue and dung in the fuelwood-deficit zones. Some countries in the Middle East also have notable fuelwood-deficit regions, and rural populations rely on alternative biofuels [*deMontalembert and Clement*, 1983]. In southeast Asia, rural populations have access to a plentiful wood supply; this is the biofuel of choice. Great quantities of unusable agricultural residue are burned in the open fields.

A variety of detailed studies and reviews are available for Asia. Biomass as rural energy is discussed in country-specific reports in a compendium by *Islam et al.* (1984); the report on Bangladesh, for example, analyzes the results of eight major surveys. *Ebinger* (1981) presents the results of a government survey that documents the fuel use patterns throughout Pakistan. *Leach* [1987] cites these studies and other surveys in his book describing household energy in South Asia. A more recent monograph on Vietnam provides data from surveys in rural and urban areas of different agro-ecological regions [*WB: Vietnam*, 1994]. For urban use, we referred to the work of *Barnes and Qian* [1992] who collected data in surveys in mid-to-large cities in Indonesia, Thailand, and the Philippines. Studies on crop residue use in the drylands of the Near and Middle East are described in *Whitman et al.* [1989] and *Papendick and Parr* [1988].

6.1. Woodfuels.

Fuelwood is used throughout Asia for cooking and also for heating, especially in the higher plateaus and Himalayan Zones. However, in some regions with abundant fuelwood, dung is customarily used as a household fuel. Grouping the developing countries of Asia into the divisions of Middle and Far East facilitates the discussion, although we note that within the two regions, woodfuels consumption habits are not homogeneous. Per capita consumption rates for countries in Asia are included in Table 7.

6.1.1. Near East and Middle East.

Here, geography ranges from the mountains and steppe to shrub deserts, with climate varying from dry to humid. Turkey, with its large natural forest areas supported by vigorous reforestation programs [*deMontalembert and Clement*, 1983], has a relatively high per capita fuelwood consumption rate (1.0 kg/capita/day). Other woodfuel consumers are Iraq, Afghanistan and Pakistan (see Table 7). These countries have fuelwood-deficit regions: high mountain zones where people have higher energy requirements, and open mixed forest-grassland and shrub vegetation zones with only a small wood supply available to the large rural populations [*deMontalembert and Clement*, 1983].

6.1.2. Far East excluding Indonesia.

The vast forest resources of southeast Asia offer a plentiful woodfuel supply, though many of these forests have been severely degraded by the densely populated rural society and other forests are almost inaccessible [*deMontalembert and Clement*, 1983]. In contrast, the hilly and mountainous countries of Nepal, Northern Myanmar, and Upper Thailand have limited fuelwood resources. Rural populations in the wood-deficit areas supplement woodfuels with crop residues and dung. Another exceptional case is the densely populated nation of Vietnam. Both rural and urban populations use fuelwood to provide energy, but the rural households also use large quantities of crop residue in all regions of Vietnam except the Mekong Delta [*WB: Vietnam*, 1994; *Tuan*, 1997].

6.1.3. Indonesia.

Wood is the dominant biomass fuel here. Few systematic surveys of woodfuel use within the densely populated rural communities of Indonesia have been reported. Many of the survey results reported in *Soesastro* [1984] describe rural communities with very different woodfuel use patterns. From these data a countrywide rural per-capita woodfuels use was calculated by combining survey information for rural West Java and other rural Java with figures for the rest of rural Indonesia, and weighting by the population of each sector. This rural per capita woodfuel consumption together with an estimate of urban woodfuel consumption taken from *Barnes and Qian* [1992] was used to calculate a weighted average of 1.0 kg/cap/day. This estimate falls in the range of reported values (0.6 to 4.0 kg/cap/day) [*Soesastro*, 1984; *WH94*; *Di Marzo*, 1994; *Kleeman*, 1994] with many values clustering about 1.0 kg/cap/day (see Table 7). Our estimate lies on the low end of the range; we feel that survey information does not support the high estimates provided in other reports.

6.2. Agricultural Residues.

From an agricultural perspective, the main features of Asia are the drylands in the Near East separated from the tropical moist regions in the southeastern portion of the continent by the unusable lands of the Himalayan Mountains [*Matthews*, 1983]. There is a concomitant variation in crops from west to east. The main crops and residues grown in the drylands of the Near East are wheat, barley and cotton. Farther east, in Iran, Afghanistan, Pakistan, and northern India, sugar cane and rice are also grown. Rice, maize, and sugar cane are the major crops in Southeast Asia [*FAO*, 1986a]. The distribution of these crop residues among the Near East, Mid East, and Far East is shown in Figure 2 (which does not include the crop residues in China and India, the dominant sources).

The farmers of the Near East and Middle East rely on the wheat and barley residues for livestock feed [*Ofori*, 1989; *Papendickand Parr*, 1988; *Jaradat*, 1988], and also use the agricultural residues as household fuel in the wood-deficit mid-Eastern region [*Ofori*, 1989]. However, the rice straw and barbojo in the southeast Asian peninsula and archipelago are generally burned in the fields [*Ponnamperuma*, 1984]. Estimates of agricultural residue burned within the regions of Asia and in the large contributing countries are presented in Table 8.

6.2.1. Near East and Middle East: Residue as Fodder.

Much of the farmland is located in rainfed drylands [*Tully*, 1989], and the main crops are wheat, barley, (Figure 2) and pulses. Almost all the straw is gathered up after harvest for winter feeding, and the remaining stubble grazed by sheep and goats [*Papendick and Parr*, 1988; *Jaradat*, 1988]. The crop residue for livestock feed is sometimes more important than the grain for human consumption [*Pearson et al.*, 1995]. In Iran, crop residues together with weeds provide about 70% of the livestock feed and are almost completely removed from the land [*Fenster*, 1989]. Within the drylands of Pakistan, no part of a crop is returned to the soil; the stubble is grazed by the livestock [*Khan et al.*, 1989]. In Turkey, one of the largest wheat producers in the Middle East, the farmers traditionally burn the wheat and barley residue in the fields (Table 8) after the animals graze [*Parr*, personal communication; *Whitman, et al.*, 1989].

6.2.2. Middle East: Residue as Biofuel.

The use of agricultural residues as fuel depends mainly on the availability of woodfuels. For the sizeable rural populations of wood-deficient countries such as Pakistan and Afghanistan, agricultural residues provide a large portion of the total biomass energy [*Khan et al.*, 1989; *de Montalembert and Clement*, 1983]. In Turkey, quantities of bagasse are used as fuel in the sugar cane processing industry.

6.2.3. Southeast Asia: Residue Burned in Fields.

Crop residue is used only in small quantities for fuel with several exceptions (see below), and the burning of dung for fuel is practically unknown in Southeast Asia [*Leach*, 1987]. In some regions large quantities of surplus rice straw are incinerated to clear the fields [*Ponnamperuma*, 1984; *Tanaka*, 1974; *Yoshida*, 1978]. In southern Vietnam and the Philippines, farmers grow more than one rice crop per year generating tons of residue which is then burned [*Nguyen*, 1994, *Yoshida*, 1978]. On the central plains of Thailand, the floating rice area and surrounding deep water areas produce rice plants more than two meters in height with significant straw waste, also burnt [*Department of Agriculture*, 1978]. Similar practices are reported for other countries in the region, including Malaysia and Indonesia, but there are notable exceptions farther north. In Japan and the Koreas, rice straw is cut close to the ground and used as compost, fodder, and fuel, but rarely burned [*Tanaka*, 1974, *Yoshida*, 1978]. In north and northeastern Thailand and northern Myanmar and Sri Lanka, the straw is cut and fed to the animals [*Department of Agriculture*, 1978; *Tanaka*, 1974]. An exception to the low residue fuel use is noted for Vietnam: in north Vietnam rice straw is a principal cooking fuel in wood-deficit rural areas [*WB: Vietnam*, 1994]. Also, in Bangladesh which has wood resources, the rural population traditionally uses residues and dung for almost half of the household fuel supply [*Islam*, 1984].

6.3. China.

China has the single largest impact on global biomass energy use. In China biofuel burning is generally confined to household use; commercial energy is used for industry [*Wen and En-Jian*, 1983]. Fuelwood is a main source of rural energy and provides about half of the total biomass consumption [*ESMAP*, 1996]. Agricultural residues supply the other half, and dried dung accounts for just one percent [*ESMAP*, 1996]. Increasingly, however, coal and electricity are replacing the fuelwood and residue use as domestic fuels, and more residue is being burned in the fields. For the model year of this paper, 1985, rural energy consumption was still based on use of fuelwood, agricultural residues and dung, and the component of excess residue burned in the fields was minimal.

6.3.1. Woodfuels.

Despite the significance of the biomass energy use in China, little information had been gathered on the structure of rural energy consumption until the mid-1980's. *Gao and Xu* [1991] presented the results of a nationwide survey in 1986 and 1987 on fuelwood consumption and fuelwood deficit estimates in 26 of 29 provinces. Their work is in contrast to previous surveys which measured only the available forest resources allocated for consumption. The results of Gao and Xu compare favorably with other national and regional figures available as shown in Table 9; figures in Table 9 are not scaled to a common year estimate. All biofuel use estimates except for one are from the 1980's; the *Gao and Xu* woodfuel estimate is mid-to-high within the range of estimates, and their residue estimate is midway within a narrow range of estimates. Gao and Xu's estimates for fuelwood consumption in rural China by province are shown in Table 10.

6.3.2. Residues as Biofuel.

Gao and Xu [1991] provided an estimate of total agricultural residue use as fuel in China. We distributed this residue fuel use in the provinces using residue availability as a guide (Table 10). However, the two northern provinces with large amounts of fuelwood available were assigned a lower residue fuel consumption, despite high residue availability; this assumption was based on the finding that fuelwood was the preferred biofuel [*ESMAP*, 1996]. The resulting distribution is supported by information on the fuelwood deficit in each region [*Gao and Xu*, 1991].

6.3.3. Dung as Fuel.

An estimate of dung use as biomass fuel was given by *Gao and Xu* [1991]. This was apportioned among the rural population in the four westernmost provinces, based on the following factors: there is major use of animal wastes for energy there [*Wen and En-Jian*, 1983], forest cover is low [*Changchun Institute of Geography*, 1990], grain production is also low, but the draught animal population is very high [*State Statistical Bureau*, 1992]. The ESMAP Study [1996] showed minimal use of dung in its survey of six counties in other provinces of China.

6.3.4. Residue Burned in Fields.

All indications are that grain residue was not burned in the fields in China in 1985; other uses such as fodder, domestic fuel, and fertilizer took priority [*Te et al.*, 1985]. To account for burning of stubble in preplant clearing, we allowed for 1% burning of all grain residue, which may be high. For the preharvest burning of sugar cane, we estimated that only 10% of the barbojo is burned in the fields [J. Kadyszewski, personal communication]. We assumed that the woody cotton stalks are used as household fuel.

6.4. India.

6.4.1. Biofuels.

Biofuel is the primary energy source in rural India. Dung use increases from south to north, agricultural residue use increases from north to south, and fuelwood consumption reaches its highest levels in the Eastern plateau and Eastern Himalayan Zones [*Joshi et al.*, 1992]. A large number of surveys and studies of rural energy consumption were conducted in the 1980s for the purposes of determining the extent of the rural energy crisis. The results of these studies were analysed by Joshi et al. [1992] as a function of agroclimatic zones, and the statewide use of each biofuel was then determined for 1991. We scaled these results to 1985 based on rural population statistics, and applied national mean estimates for Jammu and Kashmir for which no estimate was given, as shown in Table 11.

6.4.2. Residue Burned in Fields.

Crop residues are especially important as cattle feed in the semi-arid regions where much of the land is cultivated and little grassland and pasture land remains [*Rao*, 1985]. In the northern wheat and barley growing zones and in mountain villages, the straw is used for fodder [*Pal*, 1966; *J. Parr*, *J. Day*, pc, *Negi*, 1994]. The farmers of the northeastern provinces prefer to grow traditional rice with long straw as opposed to the short straw modern varieties because the straw is needed for water buffalo fodder [R. Huke, pc]. Similarly, farmers throughout India grow wheat varieties which give good returns in straw to provide fodder [*Pal*, 1966]. In the northwest, the rice straw is mixed with cow dung for use as fuel. Elsewhere, sorghum straw provides a major share of cattle feed [*Oppen and Rao*, 1982]. In some parts of India, millet is grown exclusively as a forage crop [*Sampath*, 1989]. However, residue is burned in the fields in India; for example, in Punjab [*Meelu, et al.*, 1991; *Jenkins et al.*, 1992; *Salour et al.*, 1989; *Desai*, 1985]. Rice straw in the central region around Hyderabad is also burned in the fields.

To estimate the amount of residue burned in the fields in each province in India, we used crop production data for each state (millet, Sivakumar et al. [*1984*]; maize, Reddy [*1991*]; wheat, Pal [*1966*]; rice, Pal [*1972*]; sugar cane, India [*1971*]; sorghum, Oppen and Rao [*1982*]. Joshi et al. [*1992*] provided estimates for province-by-province consumption of crop residue as biofuel. We took this into account in our assessment of how much residue would be burned in the fields. In addition, for the regions where wheat and barley residues were in abundance, we assumed most residues are used as fodder, and that only 5% is burned in the fields. Maize stalks and rice straw are more indigestible as fodder, and the burning of large quantities of rice straw is well documented; 35% of these residues was assumed to be burned based on advice from D. Pimentel [personal communication]. The cotton stalks are useful as household fuel [Townsend, pc], but, we assume a 5% burning in the fields for those areas which have other fuels, and where control of cotton pests is needed. Sugar cane is grown mainly in central and southern India, and the barbojo is needed for thatch; we assumed that 20% is burned [J. Kadyszewski, pc]. Residues of the agroindustrial processing are burned in the open (see Appendix 1).

7. Central and South America.

The biomass resources of Latin America are abundant [*deMontalembert and Clement*, 1983]. Although biofuel use dominates fuel consumption in rural areas of Latin America, these fuels provide a lower fraction of the total household energy use than in the other developing continents [*Meyers and Leach*, 1989] since the population has larger income and greater access to modern fuels [*Leach*, 1988]. In addition to sizeable forest resources and sugar cane residues available as biofuels, Latin America also has large oil supplies in the northern countries and significant hydroenergy available from the Andes mountains [*OLADE*, 1981; *deMontalembert and Clement*, 1983].

Throughout Latin America firewood is the primary source of biomass energy [*OLADE*, 1981]. Regions of woodfuel abundance are located mainly in the tropics, while zones of scarcity are found in the Andean mountains, in some arid semi-desert areas and in some of the densely populated sections of Central America and the Caribbean [*deMontalembert and Clement*, 1983]. The countries of Argentina, Brazil, Chile, Mexico, and Venezuela have established forest plantations to produce wood for paper-making, household fuel use, and charcoal production [*deMontalembert and Clement*, 1983]. Of the agricultural residues, bagasse has major significance as a biofuel, especially in Brazil [*WH94*]. Dung is also used as a household fuel in many rural highland communities [*Winterhalder et al*, 1974].

Estimates of biofuels consumption in Latin America given in Table 12 are based on data from a variety of general and country-specific reports, drawn mainly from government sources: the FAO Fuelwood Report [*deMontalembert and Clement*, 1983], the LBL [Lawrence Berkeley Laboratory] report [*Meyers and Leach*, 1989] with biofuels use estimates taken from FAO Forest Products Yearbooks and from government documents, and the energy balances report for Latin America [*OLADE*, 1981]. Other notable sources for Latin America were country-specific reports, many provided by the World Bank which contained biofuel estimates derived from detailed surveys (or projections based on earlier surveys), and data on forest resources and modern fuels available.

7.1. Biofuels in Brazil.

Brazil is the third largest biofuels consumer in the world, following China and India (see Tables 4, 7, and 13). The biofuels consumed in Brazil include wood, charcoal and bagasse and represent half of all biofuels utilized in Latin America. We used the estimates in Brasilia [*1987*] in Table 12. Brazil is the world's largest charcoal producer [*WH94*; *Brito*, 1997, *Wood and Baldwin*, 1985], and the largest global producer and consumer of bagasse [*FAO*, 1986a], which is almost entirely burned in the sugar mills [*Ogden et al.*, 1991; *DeCarvalho Macedo*, 1992].

Household consumption of biofuels versus modern fuels depends on income of the family, with firewood use decreasing as income rises [*Behrens*, 1986]. Charcoal use as household fuel is small, no higher than 9% for any income group, and generally about 1% of total household fuel use [*Behrens*, 1986]. The use of agricultural residues as household fuel is not reported.

7.2. Biofuels in other Latin American countries.

For the purposes of this discussion, the remaining countries in Latin America have been grouped into the Andean zone (including neighbors), Central America, and the Caribbean region and North Coast countries of South America. Mexico is discussed separately.

7.2.1. Mexico.

Mexico is the second highest consumer of biofuels in Latin America (Table 12) and several consumption estimates are available [*Guzman et al.*, 1987]. We relied on the summary of Martinez [1992] which describes energy use in the rural communities based on surveys in 1987 [*Secretaria de Energia, Minas e Industria Paraestatal (SEMIP)*, 1988]. For this comprehensive study, Mexico was divided into ten macroregions where energy supply and demand in the rural population is roughly homogeneous; these were divided into 38 subregions which were surveyed on both household-based and community-based energy use. The SEMIP report concluded that firewood provides about 70% of energy consumed in the rural sectors. Rural per capita fuelwood use varies significantly, from a low of 1.0 kg/cap/day in the Pacifico Norte region to 3.0 kg/cap/day in the Pacifico Sur region, depending on the abundance of wood and the need for heating. No use of agricultural residues and dung as biofuels was mentioned. However, Guzman [*1987*] noted that bagasse is burnt as fuel in the sugar mills.

7.2.2. Andean Countries and Neighbors.

Rural populations in this region rely heavily on firewood [*WB: Bolivia, 1994*; *WB: Ecuador*, 1994; *WB: Peru*, 1984; *WB: Colombia*, 1986; *Division*, 1986]. The Andean countries have considerable hydroenergy resources [*deMontalembert and Clement*, 1983; *OLADE*, 1981] that are used within the urban and commercial sectors but not by the rural population. Analysis of comprehensive surveys in Ecuador of over 1750 urban, suburban, and rural households indicated that woodfuels accounted for about 10% of urban household energy use and about 74% of rural household energy use [*Del Buono*, 1993, *WB: Ecuador*, 1994]. The highest rate of woodfuel consumption is in Paraguay (about 2.9 kg/cap/day: [*Division*, 1986]) at two to three times the rate of any other South American country [*WB: Paraguay*, 1984]. The industrial woodfuel use in Paraguay is second only to that of Brazil. This large fuelwood use may be explained by the abundant forest resources, and the low price of fuelwood compared to other Latin American countries [*WB: Paraguay*, 1984]. Per-capita consumption of fuelwood is the lowest among the rural peoples in the Altiplano region [*WB: Bolivia*, 1994], a part of the Andes which extends through Peru, eastern Bolivia and northern Chile and Argentina [*Winterhalder et al.*, 1974; *Heber*, 1986]. In these highland zones with particularly rigorous climate, wood is scarce, and dung is a main energy source [*WB: Bolivia*, 1994; *Winterhalder et al.*, 1974; *Heber*, 1986]. Dung provides some 19% of total biofuels in Bolivia [*WB: Bolivia*, 1994] and about 15% in Peru [*WB: Peru*, 1990] (Table 12). In the more densely populated urban environments of the Andean countries and their close neighbors, households also use some biofuels, less than 10% of fuel use in Ecuador [*WB: Ecuador*, 1994] and Peru [*WB: Peru*, 1990] and under 20% in Bolivia [*WB: Bolivia*, 1994]. Paraguay is an exception in that many urban households use wood [*Division*, 1986].

Charcoal is mainly consumed in the tin smelting mills in Bolivia [*WB: Bolivia*, 1994], in the steel mills in Paraguay [*WB: Paraguay*, 1984], and in the ironworks and other small urban industries in Peru [*WB: Peru*, 1990]. Charcoal is used in limited amounts as a household fuel, primarily in urban environments [*WB: Ecuador*, 1994; *WB: Bolivia*, 1994; *WB: Peru*, 1990].

Bagasse is the main residue that is burned. Some sugar cane mills use other sources of energy for processing, and burn the accumulating bagasse as a waste product [*WB: Bolivia*, 1994], but most reports suggest that bagasse is almost completely burnt as fuel in the mills [*WB: Colombia*, 1986; *WB: Paraguay*, 1984]. Other agricultural residues are burned as household fuel in Bolivia [*WB: Bolivia*, 1994] and Ecuador [*WB: Ecuador*, 1994], and coconut shells and cotton residues are burned in agroprocessing industries in Paraguay [*WB: Paraguay,* 1984].

7.2.3. Central America.

Per capita fuelwood use is higher in Central than in South America due mainly to the large forest resources. Forests cover more than 34% of the land with the exception of El Salvador [*Central Intelligence Agency*, 1991]. As in the Andean countries, fuelwood provides most of the household energy and is used largely for cooking. In Nicaragua, about 47% of the total energy requirement from 1970-1982 was supplied by woodfuels [*van Buren*, 1990]. Charcoal use is negligible in the rural regions of Central America, and is limited to the urban household and commercial sectors [*van Buren*, 1990; *WB: Honduras*, 1987; *WB: Guatemala*, 1993; *WB: Costa Rica*, 1984]. From the reports of *Bianchi et al.* [1990], consumption of agricultural residues for biofuel is dominated by bagasse; other residues used in agro-processing plants are coffee husks, coconut shells, and oil palm kernels [*WB: Costa Rica*, 1984].

7.2.4. Caribbean and North Coast.

Patterns of energy use are very similar among the Caribbean countries [*Minott*, 1992]. Biofuels are important, but the densely populated zones have limited forest resources [*de Montalembert and Clement*, 1983]. The primary energy needs are for sugar cane-processing and cooking; this explains the relatively high portion of biofuels (Table 12) supplied by bagasse and charcoal, respectively [*OLADE*, 1981; *WB: Jamaica*, 1985; *WB: Dominican Republic*, 1991; *WB: Haiti*, 1991]. The major contributor in the North Coast region is Venezuela, an oil-rich country. OLADE [*1981*] reports however, that firewood and charcoal are also used in coal plants and in the household sector.

7.3. Open-Air Burning of Residues.

Very little has been published as to the extent of open air burning of agricultural residues in Latin America. The standard practice on the sugar cane plantations is to burn the barbojo in a preharvest burn. [*De Carvalho Macedo*, 1992; *Ball-Coelho et al.*, 1993]. We assume that this is the case, unless reports indicate otherwise [*Williams and Larson*, 1993]. For Brazil, sugar cane production in each province is available [*Fundacao Instituto Brasileiro*, 1984]; we follow the suggestion of Ball-Coelho [*1993*] that sugar cane residue is burned over 90-99% of the sugar cane crop area of Brazil [Tiessen, pc] before harvest. We estimate that 50% of tobacco wastes are burned in the field as pest-control measures throughout Central and South America [*Hall et al.*, 1993]. By law, cotton stalks must be destroyed as a pest control measure in Colombia; we use the estimate of a 40% residue burn in the fields [Valderrama, pc]. For Mexico, Brazil, and Argentina, cotton stalks are mechanically destroyed and ploughed down after harvest [Jones, pc, Ramalho, pc, Cuadrado, pc]. In other countries of South and Central America farmers burn the cotton stalks in the field. Wheat residue is burned in northern Mexico [J. McIntire, pc]. The remaining agricultural residues are either used as fuel, or fodder and mulch [*Dewalt et al.*, 1993], or ploughed back into the soil [*WB: Bolivia*, 1983].

8. The Developed World.

Although the focus of this paper is the developing world, we include estimates for the developed world for the purposes of comparison (Table 13). National emission inventories for the developed world sometimes include consumption from uses of wood fuel and agricultural residue [*EPA (Environmental Protection Agency)*,1997, *Benkovitz et al.*, 1996]. While estimates for woodfuel use and residue burning in the fields are included in some tables, they are not presented in the global maps of biofuels and residue burning (Figures 4, 5, and 6).

8.1 Woodfuels.

Although developed countries are significant contributors to the global fuelwood consumption totals, wood is relatively unimportant in their energy budgets. Information on recent woodfuel use in the United States and Canada is not readily available [R. Lowe, pc; S. Phelps, pc]. The United States has estimates of state-by-state use through 1981 [*Energy Information Administration*, 1982], and also estimates for total woodfuel use in the United States, about 59 Tg residential and about 116 Tg industrial for 1985 [*Office of Technology Assessment (OTA)*, 1991]. Emissions from burning of wood fuel are included in inventories given by the Environmental Protection Agency (*EPA*, 1997). The Canadian Forest Service provides profiles of fuelwood use by province (4.8 Tg total), major consumers being paper mills in Quebec and Ontario [*Canadian Forestry Statistics 1989*, 1992]. An estimate for Australia of about 2.1 Tg woodfuels use is reported in the *Statistical Yearbook for Asia and the Pacific* [1987].

Forest residues are a nonnegligible source of bioenergy in Europe. [*International Energy Agency (IEA)*, 1987]. Information on woodfuels use in western Europe is reported in several sources [*IEA*, 1989; *International Energy Agency*, 1987; *WH94*], giving a total of approximately 100 Tg. France, Sweden, Finland, and Italy are the main contributors. For the former Soviet Union (FSU), estimates of biofuel use range from 703 PJ (about 43 Tg) for woodfuel [*Bergsen and Levine*, 1983] to 1720 PJ (in the range of 108 - 127 Tg) for all bioenergy [*WH94*]. We chose the highest estimate for fuelwood use (108 Tg), as it is our experience that most estimates for the FSU tend to be on the low side. Blandon [*1983*] indicates that about 1.3% of the fuel needs of the FSU were met by firewood. While this is not a large fraction, it provides a substantial contribution to the woodfuels burned in the developed world (390 Tg). Our estimate for the woodfuels used in the developed world is similar to that for the continent of Africa (Table 13).

8.2 Residues Burned in Fields.

In the developed world in 1985, residues were also burned at reportable levels in the fields, as discussed in Appendix 5. For Canada the only major residue subject to open field burning is wheat straw in Manitoba, Saskatchewan and Alberta [Dept of Agr: Manitoba: Virginia Knerr, pc]. In the United States, barbojo [Webb, pc] and some cereal residues are burned in the fields

[*Jenkins et al.*, 1991, Seilhon, pc]. Emissions from the burning of these residues are included in the emission inventories for the United States [*EPA*, 1997]. Many countries in western Europe ban open field burning [*Jenkins et al*, 1992]. In 1985, however, the U.K. and several Mediterranean countries (i.e. *Ezcurra et al.*, 1996) reported burning of cereal straw, ˜14 Tg residue. In Australia, residues of wheat and coarse grains, as well as sugar cane, some 7 Tg, are burnt in the fields (*National Greenhouse Gas Inventory*, 1996). The only field burning we assumed for the former USSR in 1985 was that of cotton stalks within the Central Asian Republics and as these are needed for fuel during the severe winters [Silvertooth, pc], we estimated a minimal burning in the fields of 5%.

9. Error Estimate for Biofuel Use.

The difficulties in calculating fuelwood use were described in Section 4. We assessed uncertainty in our estimates by examining both the range of per capita estimates in the regions with similar geoclimatic conditions (Tables 4 and 7) and standard deviations for per capita wood use for countries with many reported estimates. To establish the range of fuelwood use, we chose the minimum and maximum per capita use within a region as representative of all countries in the region, discarding outliers. From the regional extrema, fuelwood usage for Africa was calculated to be between 214 Tg DM/yr and 422 Tg DM/yr, compared to our best estimate of 295 Tg DM/yr, giving an error of -30% to +40%. Applying the same method to Asia, our estimate for woodfuels of 300 Tg dm/yr (excluding India and China) has a range of 181 - 585 Tg DM/yr, or -40% to +95%.

For most countries in Africa and Asia, we have too small a sample of per capita fuelwood estimates to derive meaningful statistics. We consider the sample size large enough for Nigeria, Ethiopia, Kenya, Tanzania, and Zambia in Africa. The standard deviation for Tanzania is 0.8 kg/capita/day; for the other four countries, the standard deviations cluster around 0.5 kg/capita/day. The coefficient of variation (standard deviation/mean) for these countries is between 0.2 to 0.3. These are somewhat smaller than the error estimates based on the ranges. Data is even more sparse for the countries of Asia. For Indonesia, Thailand, and Bangladesh, we compute coefficients of varation in per capita fuelwood use of 0.2, 0.5, and 0.7.

We adopted an error estimate of 40% for Africa and Asia, and also used this for Latin America, where there are very few independent estimates. Our estimates for India and China are derived from single sources. If we adopt a 40% error for China and India, and add in a 40% error in charcoal estimates for Africa and Latin America, we derive a range for woodfuel consumption in the developing world of 860 to 2000 Tg dm/yr, with a central estimate of 1430 Tg dm/yr.

The uncertainties in quantity of residue used as fuel are extremely difficult to quantify. Sources of error include crop production figures reported in *FAO* [1986a], residue-to-crop ratios, the estimates of how much residue is needed for animal feed, construction, and mulch, and the errors in the survey information we used. Clearly, the estimates of total residue production provide a rough upper limit on the amount of residue that can be burned, either as fuel or in the field. While we believe our estimates represent a significant improvement over prior work which prescribe a uniform fraction of residue to be burned, we caution that our estimates could be uncertain to at least ± 50%.

10. Spatial Distribution of Biomass Fuel Use and Burning of Agricultural Waste.

Each of these types of biomass burning: woodfuels (including charcoal), agricultural residues (including dung) as biofuel, and crop residue burning in the fields, is spatially disaggregated on a grid of 1° latitude by 1° longitude as shown in Figures 3, 4, and 5. The same color scale was used for each figure. Our major assumptions in distributing biofuels burning and open field burning are that in the developing world, biofuels are used mainly by the rural population, and that crop residue accumulates in the farming regions. The development of the 1° by 1° maps of rural population and cropland is given in Appendix 6.

10.1 Woodfuels. The 1° x 1° distribution of woodfuels (Figure 3) generally correlates with density of population, with the largest woodfuel use in southeast Asia, China, and India. In China, the most densely (rural) populated central province of Sichuan uses the most woodfuels. The northeastern province of Bihar is the largest user in India. Woodfuels are also heavily used throughout the populated regions of Africa. For Nigeria woodfuels were distributed homogeneously over the northern group and over the southern group of states, since the data was not sufficiently accurate to warrant a more detailed spatial distribution within each state. While the west coast African countries are significant consumers, the Eastern Highlands region is a hot spot for the continent, reflecting the high per-capita use there. In contrast, woodfuels are used much less in Latin America.

10.2 Residue Biofuel.

The distribution of residues used as biofuels (Figure 4) is similar to that of the woodfuels (Figure 3) because the same 1° x 1° spatial pattern was used. Comparison of the maps shows that woodfuels consumption dominates over residue fuel use in the developing world. Although woodfuels use in parts of Africa is of the same order as that in Asia, crop residue (and dung) biofuels use in Africa is much lower than that in Asia. Sichuan province in central China together with five states in the northeastern region of China have the highest biofuel use of residue in China. In the western provinces of China, where very little wood is used, dung is a primary fuel. In India wood is more uniformly used north to south, but residue use is more heavily concentrated in two northern and two southern states. In Latin America woodfuels are more heavily used than residues with the exception of Cuba where large amounts of sugar cane residue are used as fuel in the processing plants.

10.3 Residue Burned in Fields.

Open field burning in the developing world is dominated by rice straw burning in southeast Asia as shown in Figure 5. Field residue burning in Turkey and India are also significant contributors. Other obvious hot spots are the sugar cane growing provinces of Brazil, particularly the state of Sao Paulo, where over 50% of sugar cane is grown. This burning area is corroborated by satellite fire count data (ATSR World Fire Atlas, 2000) as reported in Duncan et al. [*2000*]. Large quantities of sugar cane waste are also burned in the fields of Central America (e.g., Cuba). The rest of Latin America shows minor open field burning. Similarly, in Africa, the only notable field burning occurs in the tropics; even this is relatively light.

11. Summary and Comparisons with Previous Work on Biofuels.

11.1 *Summary*

Biomass Fuel Use

A summary of our estimates of biofuel use is given in Table 13, broken down by type of fuel and by continent. The table also includes our estimates for burning of agricultural residues in the field. Our assessment of biofuel use indicates that about 2060 Tg of biomass fuel was used in Asia, Africa and Latin America in 1985 (Table 13). The majority of biomass fuel in the developing world is burned in Asia (66%), with China and India accounting for 71% of the the Asian total. Africa and Latin America use 21% and 13% of total biofuels respectively. Biofuel use in the developed world, 390 Tg, is about the same as that in Africa. Agricultural waste provided about 33% of the biofuel use in the developing world in 1985, accounting for 39%, 13%, and 29%, in Asia, Africa, and Latin America (mainly bagasse use in Brazil). In India and China, agricultural waste represents about 41% and 51% of biomass fuel, reflecting fuelwood shortage and residue availability. These figures indicating widely diverse inter- and intra-continental patterns of biofuel combustion illustrate that simple assumptions of homogeneous woodfuel and residue burning cannot account for the variations in this type of biomass burning in the developing world.

Burning of Agricultural Waste in the Fields

Crop residues burned in the fields in the developing world total about 400 Tg (Table 13). This is about 33% smaller than the amount used as biofuel in the developing world, 600 Tg. The ratio of residue used as fuel to that burned in the fields is 63:37 for Asia, 52:48 for India and 98:2 for China, and 50:50 for Latin America and Africa.

From another perspective, the residue burned in the fields is approximately 20% of the available crop residue for the developing world (Table 14), with a breakdown of 18% for Asia, 28% for Africa, and 23% in Latin America. Since the major crop producer in Asia is China, this pattern depends in large part on the practice of burning residue in fields in China (see below). Neither the average fraction for the developing world, nor those for the individual continents, reflect the widely differing practices of burning in the fields described in Sections 5 - 7. As shown in Table 8, the fraction of residue burned in the fields in Asia ranges from 1% in China, 16 - 30% in the Middle East and India, to 65% and 73% in the Philippines and Indonesia, respectively; for Africa, fractions range from 1% in the drylands in the north to 47% in the humid zone, with other regions in the 22-30% range (Table 6).

The residues which are the most significant contributors to field burning of agricultural waste are rice straw and barbojo (Table 14). While rice straw burning counts as the single largest component of agricultural burning in the fields in Asia, barbojo is the largest component in Latin America, and cereal and cotton residues the largest in Africa.

11.2 *Comparisons with previous work*

Woodfuels

Our estimate of woodfuel use in the developing world, 1324 Tg/yr, is significantly larger than the estimates of Seiler and Crutzen [1980] and Hao and Liu [1994], 743 and 620 Tg/yr respectively (Table 1). The latter addressed the tropics only, and appear to have excluded the Near East, Middle East, and China. Both of these studies relied on the statistics reported in the FAO Yearbook of Forest Products for woodfuel use, which are thought to be low, as discussed in Section 2. Consequently, Andreae [*1991*] based his estimates on an average of the FAO estimates and a universal rate of woodfuel consumption, to give overall consumption of 1260 Tg/yr. While his estimate is close to ours, it was derived to give an improved, but rough, global estimate, rather than the detailed country-by-country assessment given here. All of the estimates (Table 1) show that Asia uses over half the woodfuels in the developing world. Our estimate for

Asia (784 Tg) is similar to that of Andreae [*1991*] (858 Tg). The estimates for Latin America (Table 1) are similar because they rely primarily on government sources for information. These suggest that woodfuel use on this continent is relatively small, with the exception of charcoal use in Brazil (see Figure 3). For Africa we predict substantially higher woodfuels consumption than earlier reports, with the exception of Andreae [*1991*].

Brocard et al. [*1998*] describe domestic woodfuel use in West Africa for 1990 using various ESMAP and ENDA (Environmental Development Action) surveys for estimates of rural and urban wood and charcoal use for most countries in the region and the Silviconsult Ltd. surveys for northern Nigeria. Their rural (0.8-2.0 kg/capita) and urban (0.4-1.6 kg/capita) per capita fuelwood estimates are similar to our combined urban and rural fuelwood use (0.5-1.9 kg/capita) for the countries in the same region (see Table 4). Their total woodfuels combustion estimates for this region was 102 Tg DM, compared with our total of 113 Tg DM for the same countries.

Agricultural Residues as Biofuel

Earlier estimates of biofuel use of agricultural residues (see Section 2) assumed a uniform fraction of residue burned as biofuel in developing countries [*Hao and Liu*, 1994], or presented total residue burned as a fraction of total residue available, without regard to whether it is burned as a biofuel or field waste [*Seiler and Crutzen*, 1980, *Crutzen and Andreae*, 1990, *Andreae*, 1991]. In contrast, we have shown that the practice of residue burning varies significantly from region to region. Our results are considerably lower than those reported previously, with the exception of estimates of *Hao and Liu* [1994], as shown in Section 2. We concur with Smil [*1979*] who has suggested that crop residue is used in significant amount as livestock fodder; in some regions this precludes any burning of crop waste whatsoever.

Biofuel by Country

Some reports present country by country estimates of biofuels used in the developing world. The report of Woods and Hall [*WH94*] which does not specify the woodfuel and agricultural residue components of the biofuel use separately was described in Section 2. Streets and Waldhoff [*1998*] (henceforth *SW98*) compiled a biofuel inventory for 94 regions of Asia. Their estimates, based on information gathered from many sources (some of which were used in this work, e.g. [*Joshi et al.*, 1992] for India), provide a detailed breakdown by region of fuelwood, crop residue and animal waste as biofuels for the year 1990.

We compare the results of *WH94* and *SW98* estimated for 1990 with our work (1985) in Table 15. This comparison is given in energy units, those used by *WH94* and *SW98*, as we could not readily convert the results of *WH94* (which include all biofuels) to dry matter. The largest discrepancy between our estimates for Asia and those of *WH94* and *SW98* is that for India. While we took the TERI [*Joshi et al.*, 1992] estimates for biofuel use among the rural populations in the provinces of India (we added in Jammu and Kashmir) and scaled them only by population for 1985, *SW98* used the TERI 1995 database and added in a component of biofuel use for urban populations. This may provide a more realistic estimate, in that some portion of the urban population uses biofuels. The difficulty is in determining a good estimate of urban use. *WH94* prescribed their default urban per capita estimate to be half of their default rural per capita estimate for the developing world while *SW98* simply applied the rural per-capita rate in major cities like Calcutta. The SW98 estimate is likely to be high. A report on the fuel use in the urban area of Hyderabad suggests that biofuels are only used by one third of the urban population with the remainder using commercial fuels [*ESMAP*, 1999]. The report also estimates the urban woodfuels use in Hyderabad in 1982 to have been about 0.26 kg/cap/yr. Our estimate for India based on rural population alone is likely to be low; if we use the ESMAP [1999] per capita estimate as representative of the urban population of India, our total woodfuels use would increase by about 18 tg (or 282 PJ) for 1985. For individual countries like Indonesia and Vietnam, our results are more similar to those of *SW98* and much lower than those of *WH94*. If we project our 1985 Asia totals for the year 1990 using a simple population ratio (Demographic Yearbook [*1999*]), we estimate that 1990 Asia biofuel use would be 22,606 PJ, just higher than the estimate of *SW98* (22,000 PJ for 1990), and significantly lower than *WH94* (29,700 PJ for 1990).

For Latin America, biofuel use given by *WH94* is 10% lower than our estimate. While their estimate for Mexico is very similar to ours, their estimate for Brazil is 30% lower than ours. It is lower also than the FAO estimate for Brazil's wood and charcoal use alone.

The *WH94* biofuel estimate for Africa in 1990 is 9160 PJ, 42% larger than ours, with the largest contribution from Nigeria (2200 PJ). *WH94* takes its woodfuels use estimate for Nigeria (969 PJ) from FAO Forest Products Yearbook [1990]. The total biofuel estimate of WH94 (including residue use) is more than twice the FAO estimate for Nigeria. Our estimates of fuelwood use in Nigeria (838 PJ for 1985) were based, in part, on the Silviconsult, Ltd survey [*Hyman*, 1994], mentioned above; this survey also included an estimate of the use of sorghum stalk residue as biofuel (about 2.2 Tg, or 30 PJ) in the northern provinces where the sorghum is mostly grown. Our estimate of crop residue used as biofuel for Nigeria is about 5.5 Tg, or 74 PJ. Given the sources we have examined, it is difficult to justify the large *WH94* estimate for biofuel use in Nigeria.

Burning of agricultural waste in the fields.

Although the average fraction of residue burned in the fields in our work (20% in Table 14) is similar to the uniform fraction adopted for the developing world by Crutzen and Andreae [*1990*] (25%) and Hao and Liu [*1994*] (17%) the earlier studies cannot provide a realistic geographical distribution of very different burning practices. Comparing the developing continents (Table 14) and including China as the largest residue producer gives a range of 1 - 28 % of field burning of residues in the developing world.

12. Biomass Combustion Estimates for 1995.

Using methods for estimating biomass burning in the developing world for the target year of 1985, estimates for 1995 were calculated. For a simple update, we assumed that the changes in burning could be divided into two parts: those correlated with a change in population and those tied to changes in crop production. Our assumption is that biofuel use is proportional to population, but that the amount of residue used as agroindustrial fuel in the processing of the crop and the amount of residue burned in the fields increase as crop production increases. We give estimates for changes in quantities burned between 1985 and 1995 in Table 16.

We scaled the numbers appropriately by continent (with China, India, and Brazil estimated separately), using populations from the Demographic Yearbook [*1999*] and crop production data from FAO [*2000*]. Overall, the biomass fuel combustion increased by 20%, and residue burning in the fields by 22% for the developing world (Table 16).

Our projection for 1995 assumes that fuel availability did not change through 1995, that fuel preference did not change (no increase in use of modern fuels and corresponding decrease in biofuels), and that the habits of burning residue in the fields have been constant. This last assumption may not be reliable. The use of mechanization in agriculture is increasing, as reflected in the major increase in the number of tractors in the developing world, 40% from 1985 to 1995 [*FAO*, 2000]. One consequence of this trend is that the preharvest burning of sugar cane trash is a declining practice, at least in Brazil [H.Tiessen, personal communication], and likely in the other regions of Latin America where tractors are common. On the contrary, in China where the rural population has greater access to coal as domestic fuel, Streets et al.[*2001*] report that biofuel use has declined from an estimated 9.2 EJ in 1990 to 7.6 EJ in 2000. In addition, the organic composting of residue is declining with the increase in use of chemical fertilizers [*Zhuang et al.*, 1996]. The residue must be disposed of before planting, which could correlate with an increase in field burning. This change in practice is corroborated by remote sensing reports of increases in field burning of residues from rice, wheat, and maize in the Yangtze and Yellow River plains [*Dwyer et al.*, 2000]. In addition, a study on use of straw as fodder for ruminants estimated that about 100 Tg of straw was burned in the field in 1999 [*Suoping et al.*, 1996]. We derived an upper limit of field burning from an estimate of residue available from rice, wheat, maize, and sugar cane crops in 1995, 634Tg [FAO,*2000*] by subtracting out crop waste used as biofuel, 290Tg, and as fodder, 160Tg. We assumed that waste used as biofuel has not increased since 1985, and that 25% of crop waste is used as fodder [*Tingshuang and Zhenhai*, 1996]. Our upper limit of field burning, 185Tg, would release 9.4 Tg CO, 40% of field burning emissions of CO in the developing world in 1985.

13. Emissions.

Our estimates of trace gas emissions from biomass burning, CO_2, CO, CH_4, NO_x (Tables 17 - 21) are calculated directly from estimates of biomass burned (see Sections 4 - 7) multiplied by appropriate emission factors (Tables 22, 23, 24). A discussion of emission factors is included in Appendix 3; this appendix describes experiments measuring emissions of trace gases from combustion of wood, charcoal, agricultural residues and dung in different types of stoves in various developing countries, as well as those trace gas emissions from production of charcoal and from burning of agricultural trash in the field.

14.1. Biofuels Combustion

Our estimate for the amount of total biofuel burned in the developing world in 1985 is 1959 Tg dry matter, distributed as 61% fuelwood, 2% charcoal, 30% crop residue, and about 7% dung (Table 17). We applied the appropriate emission factors for CO_2 per species of biofuel in Table 22 to biomass burned; the resulting 2688 Tg/yr CO_2 emitted plus 41 Tg/yr CO_2 emitted in charcoal production gives about 2720 Tg CO_2 released from biofuels use in the developing world. Similarly, we estimate other trace gases emitted from biofuels use in the developing world to be 156 Tg/yr for CO (including emissions from charcoal production), 9.7 Tg/yr for CH_4, and 2 Tg/yr for N in NO_x. In making these estimates, we applied emission factors for domestic biofuels to industrial use of biofuel, since we lack data on the emissions from the latter for developing countries. This assumption most likely gives an overestimate of approximately 12 Tg/yr of CO in the developing world, as there is evidence that using charcoal in small iron blast furnaces and for the industrial processing of bagasse from sugar cane result in minimal CO emissions [Walsh, personal communication, *Kilicasian et al.*, 1999].

Differences in our estimates of trace gases emitted and those in other reports are correlated with differences either in amount of biofuel burned or in the choice of emission factors, or both.

For the region of West Africa, Brocard et al. [*1998*] reported estimates of 153 Tg CO_2 and 7.9 Tg CO released in woodfuel combustion which are similar to our values of 166 Tg CO_2 and 8.4 Tg CO for the same region. As discussed in Section 11.2, the Brocard estimates for fuel use [*1998*] are very similar to our estimates, and we use their emission factors for CO_2 and CO emitted from woodfuel burning. Their estimate of 0.32 Tg CH_4 differs from ours (0.51 Tg) in that we used a larger emission factor. In comparing our estimates of CO_2 (527 Tg) and CO (26 Tg) released from biofuel for all of Africa with those of Marufu [*1999*] 1085 Tg and 65 Tg, respectively, we note that Marufu used higher CO_2 and CO emission factors for biofuel burning (Table 22), as well as the Hall-based biofuel consumption estimates for Africa [*WH94*], notably higher than our estimates (Table 15). Olivier et al. [*1996*, *1999*] give an estimate for global emissions of CO from biofuel of 181 Tg in 1990, as part of the EDGAR 2 inventory. They relied on biofuel estimates of Hall et al. [*1994*] for the developing world, which are higher than ours as discussed above, and used emission factors of about 75 gCO/kg for wood and 45g CO/kg for agricultural waste; their wood emission factor is similar to ours, but the crop waste factor is just above half of our factor. Their estimate is similar to ours for 1985 if we allow for emissions from biofuel use in the developed world, increasing our total for 1985 from 155 Tg to 177 Tg, but the similarity is a consequence of their use of higher biofuel estimates and a lower crop waste emissions factor. The EDGAR 3 inventory has recently been released on-line, and gives estimates for CO from biofuel of 215 Tg for 1990 and 231 Tg for 1995 [*Olivier and Berdowski*, 2001; *Olivier et al.*, 2001; http;//www.rivm.nl/env/int/coredata/edgar/]. EDGAR 3 also relies on Hall et al. [*1994*] for most of the developing world, but uses the OLADE statistics for South America and emission factors given in IPCC [*1997*]. We believe that our estimates are more reliable than those given in EDGAR, because of their reliance on Hall et al. [*1994*] for biofuel use.

14.2 Emissions from Charcoal Production.

Estimates of worldwide charcoal production range from 18.7 Tg for 1985 (21.2 Tg for 1995) [*FAO*, 1998] to 100 Tg [*Smith et al.*, 1999]. The amount of CO emitted from these estimates (using the IPCC default 0.21kg pollutant/ kg charcoal produced--[*Smith et al.*, 1999]) would be 3.92 Tg and 21 Tg, respectively. Our charcoal production total is 31.6 Tg in the developing world for 1985 (Table 18) with about 5.8 Tg CO emitted from this process, using the emission factors for different types of kilns in Table 23. For the other trace gases, we estimate developing world totals of 41 Tg CO_2, 1.94 Tg/yr CO, 0.38 Tg/yr CH_4, and 0.003 Tg N from NO_x from this process. We compare our estimates for Brazil (11.4 Tg CO_2, 1.94 Tg CO, 0.38 Tg CH_4) with those of Pennise et al. [*2001*] who estimated 8.6 Tg/yr CO_2, 2.0 Tg/yr CO and 0.31 Tg/yr CH_4 emissions for 1996; we note that any agreement is fortuitous since not only are their estimates of charcoal production much lower than ours (6.4 Tg vs 11.8 Tg), but the emission factors which they used are much higher [*Pennise et al.*, 2001].

14.3 Emissions from Burning Residue in the Fields.

On a global scale, the contributions to the total annual trace gas emissions from the field burning of residues are comparatively small (0.5 Pg CO_2, 23 Tg CO, 1 Tg CH_4, and 0.2 Tg N from NO_x: see Tables 19 and 20). However, this type of burning can have major effects seasonally on a regional scale, for example, during the months of rice straw burning in southeast Asia, or sugar cane harvesting in Brazil. Clearly, the largest emissions come from Asia (rice straw), followed by emissions from the burning in Latin America (mainly barbojo), then from Africa and the developed world.

Olivier et al. [*1996, 1999*] give an estimate for CO emissions from agricultural waste burning in 1990 of 208 Tg, but this clearly reflects an error in their implementation of the results of Andreae [*1991*]. This estimate is revised to 18.6 Tg for 1990 and 16.4 Tg for 1995 in EDGAR 3 [http;//www.rivm.nl/env/int/coredata/edgar/]. Their new estimate assumes that constant fractions of agricultural waste are burned either as fuel or in the field, 30% in the developing world, and 20% in Eastern Europe and the former Soviet Union, and 5% in OECD countries [*Olivier et al.*, 2001]. Their results are of about 25% smaller than ours, and we have shown that the assumption that a uniform fraction of waste is burned is not valid.

14. Comments and Conclusions.

Biomass Fuel Use

Our assessment of biofuel use indicates that about 2060 Tg of biomass fuel was used in the developing world in 1985 (Table 13). This is equivalent to 880 Tg C (Appendix 2), and is 52% of the amount of fossil fuel burned on these continents in 1985, as shown in Table 21. We find that similar amounts of biomass and fossil fuel are burned in Africa, while in Asia and Latin America, the amount of biomass fuel is approximately half the amount of fossil fuel. Biofuel use in the developed world is about the same as that in Africa (Table 13); it is only 6%, however, of fossil fuel use in the developed world.

Emissions

The source of CO from burning of biomass fuel in the developing world, 150 Tg, is 40-50% of that from fossil fuel combustion and industrial activity for the entire world, 300-400 Tg CO, as shown in Table 20. Emissions of CO from field burning of field agricultural residues, 23 Tg, is a relatively minor source of CO, as is charcoal manufacture, 6 Tg.

The source of CO_2 from burning of biofuels in the developing world, 0.73 Pg C, is 14% of the global source of CO_2 from burning of fossil fuels. Of the biofuel source, 0.5 Pg is from burning of wood fuels, and the remainder from burning of agricultural residue and dung. The last two fuels do not provide a net source of CO_2 to the atmosphere. The impact of the wood fuels source on the CO_2 budget depends on the extent to which harvesting of wood is balanced by annual regrowth [e.g., *Houghton et al.*, 1996].

The methane source of 10 Tg from biofuel and field burning of agricultural waste is a a relatively small source of CH_4, and is much less that the source from other types of biomass burning, 23-55 Tg (Table 20). The source of NO_x from biofuel and field burning is about 10% of the source from fossil fuel combustion. However, The biofuel source may be important on a regional basis, given the short lifetime of NO_x.

Conclusions

Biofuels use in the developing world is dominated by about twenty major countries led by China, India, Brazil, and Indonesia. Realistic assessments of the current biofuels use and the trends in fuel use within these countries would be sufficient to provide a fairly good basis for estimating present and future emissions from biofuels use within the developing world.

In comparison with biofuels consumption, field burning of residue contributes a relatively small amount to trace gas emissions. However, we note that as China dominates in the production of wheat and rice, and that China is currently changing its customs of disposing of the residue from these grains and burning more in the fields, the contribution to the global trace gas emissions from the field burning of residue should increase significantly (Section 12).

Reliable estimates of trace gas emissions from biomass burning depend not only on good estimates of the amount of matter burned, but also on good estimates of emission factors from burning of household fuels together with comprehensive assessments of the conditions of domestic fuel use throughout the developing world.

Appendix 1. Agroindustrial Use of Residues.

Sugar cane bagasse is the largest category of agroindustrial residues, followed closely by rice hull residue [*FAO*, 1984, 1986]. Coconut shells, cottonseed and groundnut hulls, palm and coffee residues accrue in much smaller amounts.

For sugar cane processing we relied on the work of Williams and Larsen [*1993*]. Bagasse is used as fuel in most of the sugar factories and alcohol distilleries worldwide [*Williams and Larson*, 1993; *WB: Burkina*, 1986; *WB: Mali*, 1991; *WB: Swaziland*, 1987; *WB: Zambia*, 1983; *WB: Somalia*, 1985; *WB: Ethiopia*, 1984; *WB: Senegal*, 1983; *WB: Tanzania*, 1984; *WB: Kenya*, 1982; *WB: Uganda*, 1983]. Williams and Larsen [*1993*] indicate that factories usually are sufficiently inefficient so as to consume all available bagasse while processing the cane [c.f., *WB: India*, 1991, *WB: Burkina*, 1986], so we assume that 100% of the bagasse is burned.

Rice hulls are a low density, low nutritive byproduct of the rice-processing industry and are generally considered a nuisance [*Oyenuga*, 1968; F. A. Bernardo, pc]. In many countries, rice husks are consumed in the boilers of rice processing plants [*WB: Indonesia*, 1981, *WB: Madagascar*, 1987; Bernardo, pc]. They are also used as domestic cooking fuel [*Waddle*, 1985; *Islam et al.*, 1984; *WB: Thailand, 1985*] and for animal feed [*WB: Madagascar*, 1987], but there is also evidence that they are left in heaps to decompose [*WB: Madagascar*, 1987] or burned in the open [*Roberts*, 1973]. Estimates of how much is burned are rare. We interpret phrases such as "substantial quantities" [*WB: Thailand*, 1985] and "all" [*WB: Indonesia*, 1981] of the rice husks produced from milling operations consumed as fuel to mean 100% rice husk used in the processing plants in southeast Asia. In India, rice processing plants are frequently diesel-powered, hence, rice hulls accumulate in piles around the mill and are burnt there [R. Huke, pc]. We estimate that 40% of rice hulls are burnt outside the mills. For Africa whose rice production is only 2% of the global total the WB reports for Mali [*1991*] and Madagascar [*1987*] suggest that rice husks are used as an energy source in the factories, that small amounts are used for fodder, but that much of the residue is hauled away to decompose or burn. We assumed that 50% is used as industrial fuel, 45% is burned in the open field, and 5% is left to decompose.

Coconut residues are the most important of the minor agricultural residues. The largest suppliers of coconuts are Indonesia, the Philippines, Malaysia, and Sri Lanka. In many cases, the husks and shells are needed for open-fire drying of the copra [*Thampan*, 1987; *Pushparajah and Soon*, 1986; *WB: Western Samoa*, 1985; *WB: Tanzania*, 1984; *WB: Vanuatu*, 1985; *WB: Solomon Islands*, 1983], for the fuel in the boilers of the processing factories [*WB: Western Samoa*, 1985; *WB: Ivory Coast*, 1985], for charcoal-making [*WB: Ivory Coast*, 1985; *Pushparajah and Soon*, 1986], and for domestic fuels [*WB Benin*, 1985; *WB: Ivory Coast*, 1985; *WB: Western Samoa*, 1985]. These sources provide some data on how much husk and shell may be burned. We estimate the use of coconut residue as boiler fuel to be 50-60%, with the reminder used for open-air drying of copra. Where specific estimates are given for such uses as charcoal-making and fish-drying [*WB: Ivory Coast*, 1985], we assume these figures to be estimates of domestic fuel use.

Cottonseed hulls are burned in processing industries, mainly in vegetable oil refineries [*WB: Burkina*, 1986], but also in sugar refineries [*WB: Uganda*, 1983] and breweries [*WB: Malawi*, 1982]. Some individual reports give estimates of the amount of cottonseed husks used for agroindustrial fuel, 30-75% in Togo and ~100% in Ivory Coast [*WB Togo*, 1985; *WB Ivory Coast*, 1985]. We assumed that 75% of the waste is used as industrial fuel in cotton-growing countries where quantitative information is lacking, and that the remaining 25% decomposes or burns in the fields [*WB: Niger*, 1984].

Groundnut hulls are often used as fuel in the groundnut processing plants [*WB: Senegal*, 1983; *WB: Gambia*, 1983; *WB: Sudan*, 1983; *WB: Thailand*; 1985]. Estimates of this use vary from none in Mali [*WB: Mali*, 1991] and Guinea Bissau [*WB: Guinea-Bissau*, 1984] to 50% [*WB: Senegal*, 1983] and 100% [*WB: Gambia*, 1983]. Remaining groundnut hulls are left to decompose or burn [*WB: Mali*, 1991]. We assumed equal amounts were used as agroindustrial fuel and burned in the open (possibly near the plants) in the countries for which we had no specific data.

Coffee residues are used as fuel in the boilers of the coffee processing industry [*Silva et al.*, 1998]; in addition, the excess also accumulates at the processing mills [*Senelwa and Hall*, 1993; *WB: Ethiopia*, 1984; *WB: Ivory Coast*, 1985; *WB: Guinea*, 1986]. The detailed WB report for Ethiopia describes the practice of piling the coffee cherry skins and husks outside the decortication mills. At times, the internal temperature in the piles of husks gets so high that the decomposing mix ignites spontaneously. Several other reports indicate only minimal fuel use. In Uganda, the trucks which deliver the dry coffee cherry to the processing plants return to the farms with the coffee hulls for mulch in the coffee gardens [*Carr*, pc]. Given this qualitative information we have crudely apportioned the coffee residue use to be 50% decomposition and 50% open air burning.

Malaysia, Indonesia, and Nigeria provide 80% of the world's palm oil. In Malaysia, leftover fruit bunches are burnt on site at the mills [Philips, pc; *Husin et al.*, 1987; *Salam*, 1987]. Similarly, in Nigeria the fibre and shells are used as fuel in the steam boilers [*Omereji*, 1993]; shells are also used as artisanal and household fuels [*Ay*, 1980]. Additional detailed reports on palm oil processing in Benin [*WB: Benin*, 1985] and Togo [*WB: Togo*, 1985] suggest all residue in this industry is used for energy. We assume that 100% of palm processing residues are burned as part of the industry, except in Nigeria where we assume 100% of the empty fibre bunch and 50% the shells are burned as part of the industry, with the other 50% used for household fuel.

Appendix 2. Units and Energy Values.

To compare the amounts of biomass burned, all data were expressed in gravimetric units. We converted woodfuel amounts in volumetric units to units of weight using conversion factors of 1.4 m^3/ton (15% moisture content), or 1.5 m^3/ton, depending on whether the wood was more dense (in the more arid regions) or less dense (in regions with significant rainfall) (Openshaw, pc). If survey data included a volume to weight ratio, it superceded our default values.

Openshaw [*1986*] provides a detailed discussion of the factors influencing the energy content of various types of biofuels. The moisture content for wood, and moisture and inorganic content (ash) for crop residues and dung are the main determinants of their energy values. As the moisture content of wood varies from wet to fully dried, the energy values range from 8.2 MJ/kg to 18.7 MJ/kg [*Openshaw*, 1986]; for a default we chose 16.0 MJ/kg as the energy value for fuelwood, assuming a 15% moisture content (dry basis). For crop residue, the energy values range from 5.8 MJ/kg for fresh (100% moisture) residue with 20% ash content, to 16.7 MJ/kg for a completely dry residue with 5% ash content; for our default residue energy value we have selected 13.5 MJ/kg, for 10% ash content and 15% moisture content (dry basis). The energy values for dung range from 6.8 MJ/kg for wet matter and 25% ash content to 17.0 MJ/kg for totally dry matter and 20% ash content; we chose as default, 14.5 MJ/kg. For conversion to amount carbon per amount dry matter, we used the multiplicative factors 0.45 gm C/gm DM for wood, 0.40 gm C/gm DM for crop residue, and 0.35 gm C/gm DM for dung [*Smith et al.*, 2000], unless other conversions were indicated.

Appendix 3. Emission Factors.

The emission factors of trace gases from biomass combustion are influenced by several factors including the actual amount of carbon in the preburned dry matter, the size, shape and moisture content of the sample, and the flaming versus smoldering pattern of the burning process [*Ward et al.*, 1996]. Most published emission factors are based on emission ratios using a carbon balance method which requires knowing the carbon content of the fuel. The carbon content of the biomass fuel is inversely proportional to the moisture content and the non-carbon ash content [*Smith et al.*, 1993] which can range from 0.3% by weight (dry basis) for ponderosa pine to 24% for rice straw left in the field over the winter [*Jenkins and Ebeling*, 1985]. Carbon in the preburned biofuels or residue can vary from 35% by weight (for rice straw: *Jenkins*, 1993) to 54% (South Africa leaves, *Susott et al.*, 1991), but is often assumed to be about 50% [*Marufu*, 1999, *Smith et al.*, 1993]. Errors in the assumed carbon content can lead to discrepancies in emission factors calculated using the carbon balance method. This method equates the total carbon in the preburn fuel to the sum of carbon in all its postburn forms, from the charred uncombusted fuel to the volatiles [*Ward and Radke*, 1993; *Smith et al.*, 1993]. Published emission factors for CO_2 are 1393 - 1620 gm pollutant/kg biofuel with carbon content ranging from 41.8 - 50 % [*Smith et al.*, 2000; *Zhang et al.*, 2000; *Brocard et al.*, 1998; *Smith etal.*, 1993; *Marufu*, 1999]; if we adopt a 50% carbon content, the emission factor range is reduced to 1551 - 1664 gm CO_2/kg biofuel. The distribution of carbon in the products from biomass burning: CO_2, CO, CH_4, NMHC, TSP, ash, and uncombusted fuel, is strongly influenced by the temporal pattern of flaming and smoldering (more and less efficient combustion, respectively) in the burning process [*Brocard et al.*, 1998, *Marufu*, 1999, *Jenkins and Turn*, 1994, *Ward, et al.*, *1996*].

Biofuels.

Several groups have designed experiments which replicate conditions commonly found in the combustion practices in developing countries in order to characterize emission factors for biofuels [*Zhang et al*, 1999; *Brocard et al.*, 1998; *Marufu*, 1999; *Bertschi et al.*, 2002]. Marufu and Brocard et al. used stoves common to Zimbabwe and West Africa, depression-in-the-ground and three-stone stove, respectively; Zhang et al. [*1999*] examined burning of 56 combinations of fuels and stoves commonly used in India and China, and Bertschi et al. [*2002*] studied traditional cooking fires in rural Zambia.

We display the results reported by these and other groups in Table 22. We included the percent carbon measured or assumed for the biofuel in the first column, if available. Marufu [*1999*] assumed 50% carbon; we used the carbon balance to calculate the CO_2 and CO emissions if he had assumed the values of Zhang et al. [*2000*] and Smith et al. [*2000*]: 45% C in fuelwood, 33.4% C in dung and 34.8% C in maize residues. Using the measured carbon content brings the results of Marufu closer to those of Zhang et al. [*2000*] and Smith et al. [*2000*], except for crop residues. In comparing emission factors in Table 22, we observe that the range of factors reported from the experiments of Zhang et al. [*2000*] and Smith et al. [*2000*] encompass the factors published in the other reports, at least for fuelwood combustion. We note that within the developing world, domestic fuel burning involves using wood with different carbon and moisture content with different methods of flaming and smoldering, depending on the need to conserve fuel; we do not have information on the how these variables change, region to region. The experiments described above use various techniques to measure the products of burning and make different assumptions of carbon dispersal. More careful assessment of traditional practices of household fuel use in the developing countries is needed, together with corresponding experiments to monitor trace gas emissions from this burning.

To derive estimates of these emissions, we propose the following: biofuels used in household combustion are usually air-dried (giving them higher moisture content than oven-dried samples used in experiment) and also frequently include brush and twigs with higher ash content (Jenkins, personal communication) which argues for fuel with a lower carbon content; we selected 45%. We then chose the emission factors of Brocard et al. [*1998*] from experiments in West Africa of 1467 and 70 gms pollutant/kg dry fuel for CO_2 and CO, respectively; these are close to averages of the mean for India [*Smith et al.*, 2000] and for China [*Zhang et al.*, 2000] (Table 22). For the emission factors of CH_4, NO2, and TSP, we averaged the mean values of Smith et al. [*2000*] and Zhang et al. [*2000*], since Zhang et al. [*2000*] note that these fuel/stove combinations represent a large fraction of combinations in use worldwide. The spread of values for emission factors of CH_4 and NO_x is much larger than those of CO.

The charcoal burning emission factors are taken from the results of Smith et al. [*1993*] except for NO_x which is from the review of Andreae and Merlet [*2001*]. Two independent studies on combustion of dung [*Smith et al.*, 2000, *Marufu*, 1999] give very similar emission factors for CO and CO_2, when adjusted to the correct carbon content; we chose the values from Smith et al. [*2000*]. For the other gases, we used the work of Andreae and Merlet [*2001*]. While the range of values for residue burning is large, mean emission factors for CO_2 and CO from combustion of rice straw, mustard stalk, maize residue, and wheat straw are similar. We used the Zhang et al. [*2000*] values for all emission factors, except for CO_2; for this we took the Smith et al. [*2000*] as it is close to the other results given in Table 22.

Charcoal Production.

Emissions of atmospheric gases during charcoal production depend on the type of kiln used [*Openshaw*, 1986, *Smith et al.*, 1999], as well as the type and moisture content of wood used, and the skill of the operator [*Foley*, 1986, *Openshaw*, 1986]. Since emission factors are often expressed as amount of trace gas per amount of charcoal produced, and information on charcoal production is given in terms of amount of wood used for charcoal production, knowing the efficiency of the conversion process is essential to calculate the trace gas emissions. Kilns in the developing world range from the traditional earth mounds or pits with efficiencies as low as 10% [*Foley*, 1986] to industrial kilns with efficiencies of up to 33% [*WH94*].

In Africa, the earth mound kiln is used almost exclusively (Africa: *Smith et al.*, 1999, West Africa: *Brocard et al.*, 1998, Zambia: *Hibajene et al.*, 1993, Malawi: *Openshaw*, 1997, Kenya: *Kituyi et al.*, 1999, *Pennise et al.* , 2001, Senegal and Tanzania: *Foley and van Buren*, 1982). From World Bank reports for the 1980's the estimates of efficiencies for these kilns varied from 9% to 20%, and were lower than those given in the 1990's (20-29%) [*Smith et al.*, 1999; *Brocard et al*, 1998; *Openshaw*, 1997; *Hibajene*, 1993]. We chose an estimate of 15% efficiency (20% efficiency for Sudan) for our charcoal numbers for 1985, and used the emission factors of Brocard et al. [*1998*] as representative of all the kilns in Africa (see Table 23).

Smith et al. [*1999*] described the types of charcoal kilns used in Thailand and suggested that these are representative for Asia; the efficiencies of these kilns ranged from 29.4 to 33.3%. From other sources, we have estimates of 18 - 25% efficiency for kilns in Asia [*WB: Vietnam*, 1994; *WB: Burma*, 1985; IPCC Reference Manual in *Smith et al.*, 1999]. We chose an efficiency of 25% for Asian kilns, unless specified for an individual country and used the charcoal production emission factors from Smith et al. [*1999*] (see Table 23).

Most of the charcoal used commercially in Brazil is produced in brick or mud beehive kilns which have an efficiency of 33% [*WH94*]. We used emission factors for production in brick beehive kilns from Smith et al. [*1999*] for Brazil, as well as for the commercially produced charcoal for the steel and iron industries of Bolivia, Peru, and Paraguay. The recent report of Pennise et al. [*2001*] presents studies on emissions from Brazilian kilns which may provide more realistic emission factors than those we chose. For charcoal produced for domestic use in Latin America, we adopted the kiln efficiency of 17% reported in *van Buren* [1990] and used the IPCC (1997) default world average emission factors (Table 23).

Open Field Burning.

The emission factors for CO_2 from residue combusted in the open field (Table 24) are similar to those for residue used as biofuel (Table 22). The open field burning emissions of CO and CH_4 tend to be much lower than those measured for biofuel. Given that the moisture and ash content are very similar (*Jenkins and Turn*, 1994; *Zhang et al.*, 2000), we can explain the differences by postulating that a larger proportion of uncombusted fuel remains. A variety of techniques have been used to measure emissions from burning of agricultural waste. Ezcurra et al [*1996*] used an aerosol dilution chamber to burn samples of cereal straw while Jenkins and Turn [*1994*] burned samples of barley, corn, rice, and wheat residues on a conveyor belt in a combustion wind tunnel; Nguyen et al. [*1994*] measured gaseous emissions during burning of rice straw out in the fields in both the wet and dry seasons, but did not provide the biomass loading.

We present all emission factors in units of gm pollutant/kg dry matter to be burnt in Table 24 and compare the values for straw burning with estimates for mean values for savanna burning given by Andreae and Merlet [*2001*]. The residues which are the most significant contributors to field burning of agricultural waste are rice straw and barbojo (see Table 14). We determined emission factors for the burning gases by weighting the emissions factors for rice straw [*Jenkins and Turn*, 1994], barbojo, and other cereals by the fraction of global burning in fields ascribed to the three components (weighting of 40:31:20 %) Our chosen emission factors fall within the ranges presented in Table 24 for CO_2 and CO, are somewhat high for NO_x (reflecting the dominant rice straw burning), and are typical for TPM.

Appendix 4. Decomposition.

Decomposition of residues left in the fields after harvest is influenced by substrate composition and the environment, particularly temperature and moisture [*Bell*, 1974]. The tropical regions provide optimal conditions for microbial decomposition of plants. In a simple view, the sequence of the breakdown of plant matter is that the soluble organic matter (the carbohydrates in the form of starches and sugars) decompose most rapidly, followed by the proteins in the form of cellulose and hemicellulose, and finally the woody part of the stalk, known as lignin [*Bell*, 1974]. Since the leafy portion of the residue decomposes very quickly in the tropical rain forest [*Bates*, 1960] (100% decomposition), we confine our discussion to the stalks and straw of four major crops: maize, millet, sorghum, and rice.

For all four types of stalk and straw we assume that the soluble organic matter totally decomposes between the crop harvest and the next preplant burn [*Martin et al.*, 1942; *Satchell*, 1974], and that the lignin portion of the residue (about 10%) remains almost entirely intact [*Martin et al.*, 1942] and burns in the pre-plant burn. The remaining matter, the hemicellulose and cellulose portion, only partially decomposes [*Swift et al.*, 1979].

For the case of the maize stalks, lignin represents about 8.5% of the dry weight of the stalk [*Muller et al.*, 1971], hemicellulose about 18%, and cellulose about 30% [*Swift et al.*, 1979]. From experiments on decomposition rates over 40% of the cellulose and hemicellulose have decomposed after 30 days [*Swift et al.*, 1979]. Using these data, we estimate that 62% (including the soluble organic matter) of the stalks left in the fields decompose, and that the remaining 38% is burned before planting.

The soluble cell content of millet straw is approximately 24% and that of sorghum straw about 30% [*Reed*, 1992; *Alhassan*, 1990]. Assuming that 40% of the hemicellulose and cellulose decomposes for these residues also, we estimate that 52% of millet and sorghum stalks decompose, and 48% burn in the fields.

Quantitative information on the decomposition of rice straw was unavailable, so we based our estimates on wheat straw [*Swift et al.*, 1979], for which about half the straw decomposes. The remaining 50% is assumed to be burned in the fields, unless other information is available. For the southeast Asia region where several rice crops are grown per year, we presume that with no time for decomposition of the residue, most of the rice straw is burned.

Appendix 5. Open Field Burning in the Developed World.

Here we discuss burning of crop residue in the United States, Canada, countries in Western Europe, and countries of the former Soviet Union (FSU).

Open field burning of barbojo and cereal residues occurs in parts of the United States. About 90% of the barbojo is burned in the four sugar cane producing regions (Hawaii, Puerto Rico, Florida, Louisiana) [Walter Webb, pc: Paul Seilhon, pc]. Of the cereals, over one Tg of rice straw, ~90%, is burned in California [*Jenkins et al.*, 1991; Seilhon, pc (EPA report of 1992)], but only small amounts are burned in the southern states (e.g. 7.5% in Louisiana, 1% in Texas), due to the much faster decomposition of the straw in the warmer, wetter climate of the south (P. Seilhon, pc). Estimates of the burning of wheat stubble for 1985 range from minor (0-5%) in the southwestern states of Colorado, Arizona, and New Mexico (R. Young, pc) to 5-20% in Missouri, Kansas, Louisiana, Tennessee (Fjell, pc; R. Fears,pc), to ~30% in Montana and North Dakota where it is colder and drier and decomposition is slow [Knerr, Gallatin County Extension, pc]. Corn residue in the midwest states is left to decompose in the fields (Dudley, pc). Cotton stalks in Texas and California are ploughed under to prevent growth of pests [Crane, pc; *Jenkins et al.*, 1991]. Grass-seed residue is burned in Oregon, the major grass seed producer in the U.S. [R. Fears, pc; W. Young, pc: *Young*, 1998].

The major grain-producing provinces in Canada are the large wheat-growing states of Manitoba, Saskatchewan, and Alberta. Estimates of wheat straw burned are less than 10% for 1985 [Agricultural Representative: Dept of Agriculture, Manitoba].

The agricultural wastes burned in Australia are residues of wheat, coarse grains, and sugar cane [*Hurst et al.*, 1995; *NGGIC*, 1996, *Gupta et al.*, 1994; *Canteromartinez et al.*, 1995]. We used the state-by-state profiles of crop production for 1990 of the Australian National Greenhouse Gas Inventory [*NGGIC*, 1996] for distributing the FAO estimates of Australian production of wheat, coarse grains, and sugar cane in 1985 (*FAO*, 1985). In addition, the inventory contained estimates of residue-to-crop ratio, per cent dry matter, and fraction of residue burned in the field for each crop. We used these estimates in constructing our distributions of agricultural waste burned in the fields, even though, in the case of sugar cane, there were unresolved differences between estimates of the Australian NGGIC (*1996*) and the ones suggested by the United States EPA (*EPA*, 2000).

There is a general trend to prohibit burning in western Europe [*Jenkins et al.*, 1992]. However, in the United Kingdom up to 1989, approximately 30% of barley and wheat straw residue (or about 6 Tg) was burned annually [*Jenkins et al.*, 1992]. *Ezcurra et al.* [*1996*] document the burning of more than 6 Tg of cereal waste in Spain. In Greece, the burning of up to 80% of wheat straw (about 2 Tg) occurs [Kalburtzi, pc; *Kalburtzi et al.*, 1990].

For the FSU in 1985, a portion of the crop residue was used as animal fodder [S. Zhourek, pc]. Much of the remaining residue is taken off the field and piled in heaps and left to decompose. In Kasakhstan, combines collected the straw and left it in piles and the leftover stubble was ploughed under; the rice straw in the Dnieper River region was not burned [K. Gray, personal communication]. We assumed that the cotton stalks were burned mainly as fuel, but in minor amount as trash in the fields; since 80% of the FSU cotton was grown in the five Central Asian Republics [*FAO*, 1995], we have concentrated it there. From recent AVHRR data composite fire images over southern Russia indicate major burning (C. Heald, pc) in March; these fires might be preplant burning of agricultural trash leftover from the previous year's harvest. More careful analysis is needed to determine if this should be added in to the agricultural residue burning estimate.

Appendix 6. Spatial Distribution of Biofuel Use and Agricultural Waste Burning.

Biofuel use within each country (and province for China, India and Brazil) was spatially distributed using a map of rural population density that we developed specifically for this purpose. We used a digital data base developed at the NASA Goddard Institute for Space Studies [*Lerner et al.*, 1988], which labels each land 1° x 1° cell of the world with a code identifying the country. China, India and Brazil are sub-divided into their major political entities. National populations for 1985 were taken from the UN Demographic Yearbook [*1992*], and those for the subdivisions from Encyclopedia Brittanica [*1987*]. The rural fraction of the population, and the agriculturally active population in each country was taken from the same sources.

Two other global 1° x 1° data bases were used to distribute the rural population within each country, the first to identify habitable land [*Lerner et al.*, 1988], and the second to locate regions of crop production [*Ramankutty and Foley*, 1998]. Habitable land was identified using a data base developed for the purpose of locating animals; in this case, each grid cell was assigned to use either by animals, lumber industry, ice, or no use at all [*Lerner et al.*, 1988]. We considered grid cells designated as animal use and lumbering to be habitable. In countries which would contain no habitable area in this plan, we reassigned certain cells as habitable based on published population maps [e.g. *Times World Atlas*, 1990]. The locations of agriculture were identified using a global map of croplands distribution that detailed the crop fractions within gridboxes of five minute by five minute resolution; these had been determined by analyzing seasonal variations in vegetation indices for AVHRR data [*Ramankutty and Foley*, 1998]. We note that although the cropland cover within a gridbox provides a suitable surrogate for locating the farming population of a country, it does not give information as to the density of the agricultural population or the density of crops. This is a source of error in distributing both the biofuel use (population based) and amount of residue burned in the fields (crop based).

We assume that the major users of biofuels are the rural population. Within each country, the agriculturally active portion of the population was distributed equally within the agricultural cells and the remaining rural population was apportioned over all habitable cells. For China, India, and Brazil, the population was distributed in the appropriate province. The burned biomass in each country (or province) was then spread among the appropriate cells using the population density, to generate Figures 3-5. The burning of crop residues in the fields was distributed directly according to the croplands map [*Ramankutty and Foley*, 1998].

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Figures List.

Table 1. Fuelwood Combustion (Tg DM)

	Seiler and Crutzen (1980)	Crutzen and Andreae (1990)	Andreae (1991)	Hao and Liu (1994)
Developing				
Africa	182	-	240	180
Asia	397	-	858	320
Latin America	164	-	170	120
SubTotal	743	-	1260	620
Developed	113	-	-	-
Totals	856	1050	1430	-

Table 2. Geographic Distribution of Available Residue for Developing Continents
(Per Cent of Total)

	Cereals				Cotton	Sugar Cane	Minor Agro Industry	Total
	Maize & M&S*	Wheat & Barl	Rice	Total Cereals				
ASIA	13	13	39	**66**	**5**	**6**	**1**	**78**
China	8	6	15	**29**	**3**	**1**	**0**	**33**
India	3	3	8	**14**	**1**	**3**	**0**	**18**
S AMERICA	5	1	1	**7**	**1**	**5**	**0**	**13**
Brazil	2	0	1	**3**	**1**	**4**	**0**	**8**
AFRICA	5	1	1	**7**	**1**	**1**	**0**	**9**
TOTALS	24	16	40	**80**	**7**	**12**	**1**	**100**

*M&S = Millet and Sorghum

Table 3. Residue-to-Crop Ratios

Crop	Selected Value	Range	Barnard and Kristofferson	References
Wheat Res	1.3	0.9-1.6	0.7-1.8	1,2,3,4
Maize Stlks	2.0	0.9-4.0	1.2-2.5	5,2,4,6,7,8,9
Rice Husks	0.2	0.17-0.22	0.3	10,7,8,9,11,12
Rice Straw	1.5	0.8-2.5	1.1-2.9	13,2,6,7,9
Barley Res	1.6	1.4-2.0	0.9-1.8	14,4,5
Millet/Sorghum Stlks	2.0	1.5-3.7	2.0-4.6	9,2,5,7,8,15
Sugar Cane Bagasse	0.15	0.05-0.2	-	3,16
Sugar Cane Barbojo	0.17	0.09-0.28	-	3,16
Cotton Hulls	0.26	-	-	9
Cotton Stlks	4.0	3.0-5.5	3.5-5.0	21,2,5,6,15
Groundnut Shells	0.4	0.25-0.5	0.5	17
Coffee Res	0.92	0.3-1.8	-	18,8,15
Coconut Shells+	1.9	-	0.7-4.5	19
Palm Empty Fibre Bunch	0.39	-	-	20
Palm Fibers	0.4	0.2-1.1	-	20
Palm Shells	0.23	0.2-1.0	-	20

1) Hall et al. (1993), (2) Poulain (1980), (3) Williams and Larson (1993), (4) World Bank (WB): Morocco (1984), (5) Senelwa and Hall (1993), (6) WB: Mali (1991?), (7) WB: Guinea (1986), (8) WB: Madagascar (1987), (9) WB: Senegal (1983),(10) Waddle (1985), (11) Roberts (1973), (12) Bernardo pc (199?), (13) Ponnamperuna (1984), (14) Based on Williams and Larson (1993), (15) WB: Ethiopia (1984), (16) Kadyzewski pc, (17) Based on WB: Guinea (1986) and WB:

Mali (1991?), and WB: Senegal (1983), (18) WB: Ivory Coast (1985), (19) Use Barnard and Kristofferson (1985), (20) Calculations based on Husin et al. (1987), Salam (1987), and Shamsuddin and Nor (1987).

Table 4. Fuelwood Use in Africa

Country	Totals (Tg dm/yr)	Per Capita (kg/cap/day)	Other Estimates	References[a]
N DRYLANDS				
Algeria	7.34	0.92	-	1
Egypt	0.88	0.05	-	1
Libya	0.00	0.00	-	1
Mauritania	0.66	1.02	-	2
Morocco	6.7	0.78	1.4	3,1
Tunisia	1.11	0.42	0.8	4,1
W. Sahara	0.00	0.00		
TOTAL	16.26			
SAHEL				
Chad	0.55	0.30		5
Mali	4.46	1.49	0.8,1.2,1.5,1.8,2.5	6,7,7,8,7,7
Niger	2.82	1.17	1.4	7,9
Senegal	1.15	0.48	0.2,1.4,1.6	11,7,10,7
Sudan	18.16	2.28	1.0,1.4,1.9,2.6	78,5,12,13,80
TOTAL	27.14			
WEST COAST				
Benin	1.92	1.30	-	15
Burkina Faso	4.94	1.70	1.5,1.6,2.0	16,17,7,7
Gambia	0.63	2.33	1.9,2.3,2.4	19,18,13,14
Ghana	7.94	1.71	1.1,1.2	20,21,7
Guinea	5.48	3.22	3.0	22,23
Guinea-B	0.39	1.22	-	24
Ivory Coast	5.69	1.57	0.8,1.2	21,25,7
Liberia	1.79	2.24	0.6,3.7	26,7,7
Nigeria	52.39	1.50	1.0,1.2,1.7,1.9,2.0,2.7	75,7,7,27,28,14,14
Sierra Leone	2.03	1.58	1.9,2.2,2.5	29,21,7,7
Togo	1.55	1.40	-	30
TOTAL	84.75			
CENTRAL AFRICA				
Angola	6.33	1.98	1.2	31,32
Cameroon	5.90	1.59	5	
Cen. Af. Rep.	1.89	1.99	5	

Congo	1.14	1.61	1.1,1.5	21,33,21
Eq. Guinea	0.29	2.54	-	5
Gabon	0.58	1.61	0.7	70,71
Zaire	17.41	1.54	1.5	34,5
TOTAL	33.54			
E HIGHLANDS				
Kenya	14.03	1.89	1.9,2.0,2.1,2.2, 2.7,2.9,3.1,3.3	74,13,14,73,14, 37,21,35,38
Malawi	7.91	3.07	2.7,3.4	39,28,40
Tanzania	25.46	3.21	2.2,3.1,3.5, 4.0,4.4	76,13,41,28, 41,13
Uganda	12.45	2.18	2.6,2.7,3.0	42,43,36,13
Zambia	7.95	3.24	1.9,2.3,2.4,3.2	79,46,45,28,44
TOTAL	67.80			
E&S DRYLANDS				
Botswana	0.80	2.04	1.3,2.3,2.8	50,48,49,47
Burundi	2.15	1.25	0.4	72,51
Ethiopia	29.11	1.84	0.7,1.5,1.6	52,53,5,21
Lesotho	0.03	0.05	0.1,1.2	54,5,55
Mozambique	8.37	1.66	3.1	56,57
Namibia	0.28	0.50	-	58
Rwanda	3.85	1.73	1.1	48,59
Somalia	2.28	0.98	-	60
South Africa	9.08	0.79		79
Swaziland	0.30	1.28	1.1	61,28
Zimbabwe	4.70	1.55	1.7,1.8	62,28,63
TOTAL	60.95			
ISLANDS				
CapeVerde	0.09	0.77	-	64
Comoros	0.28	1.66	-	65
Madagascar	3.43	0.94	-	66
Mauritius	0.23	0.63	0.0	67,5
SaoTome&	0.10	2.56	-	68
Seychelles	0.00	0.25	-	69
TOTAL	4.13			
AFRICA TOTAL	294.57			

(a)Explanation of References

1)de Montalembert and Clement (1983), (2) World Bank (WB): Mauritania (1985), (3) WB: Morocco (1984), (4) WB: Tunisia (1992), (5) Meyers and Leach (1989) mostly from FAO Year-book of Forest Products, (6) WB: Mali (1992), (7) Kahane and Lwakabamba (1990), (8) WB: Mali (1991), (9) WB: Niger (1984), (10) WB: Senegal (1983), (11) Lazarus, et al. (1994), (12) Abu Sin and Davies (1991), (13) Arnold and Jongma (1978), (14) Moss and Morgan (1981), (15) WB: Benin (1985), (16) WB: Burkina (1986), (17) Ernst (1977), (18) WB: The Gambia (1983), (19) Openshaw (1978), (20) WB: Ghana (1986), (21) Davidson (1992), (22) WB: Guinea (1986), (23) WB--Guinea ?, (24) WB: Guinea-Bissau (1984), (25) WB: Ivory Coast (1985), (26) WB: Liberia (1984), (27) WB: Nigeria (1993), (28) Raskin and Lazarus (1991), (29) WB: Sierra Leone (1987), (30) WB: Togo (1985), (31) WB: Angola (1989), (32) Bhagavan (1984), (33) WB: Congo (1988), (34) WB: Zaire (1986), (35) Senelwa and Hall (1993), (36) Cecelski et al. (1979), (37) WB: Kenya (1982), (38) O'Keefe et al. (1984), (39) WB: Malawi (1982), (40) Scobey (1984), (41) WB: Tanzania (1984), (42) WB: Uganda (1983), (43) Bashou (1990), (44) WB: Zambia (1983), (45) Hibajene et al. (1993), (46) Ng'andu (1990) based on FAO, (47) WB: Botswana (1984), (48) Hall and Mao (1994), (49) Diphaka and Burton (1993), (50) Wisner (1984), (51) WB: Burundi (1982), (52) WB: Ethiopia (1984), (53) Hall (1991), (54) WB: Lesotho (1984), (55) Frolich (1984), (56) WB: Mozambique (1987), (57) O'Keefe and Munslow (1984), (58) WB: Namibia (1993), (59) WB: Rwanda (1982), (60) WB: Somalia (1985), (61) WB: Swaziland (1987), (62) Hemstock and Hall (1997), (63) WB: Zimbabwe (1982), (64) WB: Cape Verde (1984), (65) WB: Comoros (1988), (66) WB: Madagascar (1987), (67) Baguant (1992), (68) WB: Sao Tome (1985), (69) WB: Seychelles (1984),(70) Same as Congo, (71) WB: Gabon (1988), (72) Same as Zaire, (73) Banwell and Harriss (1992), (74) Estimate based on Hosier (1985), O'Keefe and Raskin (1985), Kituyi et al. (1999), (75) Estimate based on Hyman (1994) and Kersten et al. (1998), (76) Estimate based on data in Hosier et al. (1990), (77) Woods (1990), (78) Estimate of Keith Openshaw based on data in WB Sudan (1983), (79) Scholes and van der Merwe (1995), (80) Mukhtar (1978)

Table 5. Charcoal Use in Africa

Country	Total Wood needed (Tg)[a]	Choice kg charcoal/ urbancap[b]/ yr	Other Estimates	References
Eastern Highlands				
Burundi	0.2	165	-	1
Kenya	6.4	283	306,459,562,594	46,2,3,4,5
Mozambique	2.6	217	-	6
Rwanda	0.4	197	-	7
Tanzania	4.5	177	125,170,187,290,353	44,6,6,2,8,6
Uganda	1.9	192	184	9,2
Zambia	5.1	256	160,168,158	45,10,6,11
Total	21.1			
Southern Drylands				
Namibia	0.0	8	-	14
Zimbabwe	0.0	1	-	12
Others[c]	0.0	0	7,12,13,15	
Total	0.0			
Sudan[d]	15.0	667	420	16,6
Rest of Africa				
Angola	1.3	73	185	17,18
Benin	0.1	27	-	19
Burkina Faso	0.1	12	-	10
Cameroon	0.6	24	-	20
CapeVerde	0.0	3	1	10,21
Cen. Af. Rep.	0.4	49	-	20
Chad	0.4	53	-	15
Comoros	0.0	1	-	22
Congo	0.3	40	10	20,23
Djibouti	0.1	28	-	15

Egypt	0.1	1	-	15
Eq. Guinea	0.1	125	-	20
Ethiopia	1.3	43	36	24,4
Gabon	0.0	3	-	20
Gambia	0.0	22	-	15
Ghana	3.0	110	-	25
Guinea	0.5	57	-	26
Guinea-B	0.1	61	-	27
Ivory Coast	1.1	41	-	28
Liberia	0.7	189	-	29
Libya	0.1	4	-	15
Madagascar	1.2	84	-	30
Malawi	0.6	103	-	43
Mali	0.4	34	-	31
Mauritania	0.1	143	44	10,32
Mauritius	0.0	9	-	15
Morocco	0.8	13	-	33
Niger	0.0	4	-	34
Nigeria	1.2	12	-	15
Reunion	0.0	7	-	15
SaoTome&	0.0	41	-	20
Senegal	1.8	162	82,115	15,35,36
Sierra Leone	1.0	169	63	15,37
Somalia	1.2	113	55	15,38
Togo	0.3	110	-	39
Tunisia	0.2	7	-	40
Western Sahara	0.0	6	-	41
Zaire	4.0	49	52	15,42
Total	23.1			
TOTAL AFRICA	59.2			

(a)Assume 15% efficiency in converting wood to charcoal (b)Charcoal is mainly an urban phenomenon in Africa. (c)Botswana, Lesotho, South Africa, Swaziland (d)Assume 20% efficiency in converting wood to charcoal

(1) World Bank (WB): Burundi (1982), (2) O'Keefe (1990), (3) Senelwa and Hall (1993), (4) Meyers and Leach (1989), (5) WB: Kenya (1985), (6) Foley (1986), (7) Hall and Mao (1994), (8) Tanzania Energy Dept (1989), (9) WB: Uganda (1983), (10) Barnes and Qian (1992), (11) Hibajene et al., (1993), (12) Hemstock and Hall (1997), (13) Frolich (1984), (14) WB: Namibia (1993), (15) KOpenshaw pc, (16) WB: Sudan (1983) and assuming 20% efficiency in charcoal production, (17) WB: Angola (1989), (18) Bhagavan (1984), (19) WB: Benin (1985), (20) World Wildlife Fund (1993), (21) WB: Cape Verde (1984), (22) WB: Comoros (1988), (23) WB:

Congo (1988), (24) WB: Ethiopia (1984), (25) WB: Ghana (1986), (26) WB: Guinea (1986), (27) WB: Guinea-Bissau (1984), (28) WB: Ivory Coast (1985), (29) Kahane and Lwakabamba (1990), (30) WB: Madagascar (1987), (31) WB: Mali (1991), (32) WB: Mauritania (1985), (33) WB: Morocco (1984), (34) WB: Niger (1984), (35) Lazarus (1994), (36) WB: Senegal (1983), (37) WB: Sierra Leone (1987), (38) WB: Somalia (1985), (39) WB: Togo (1985), (40) WB: Tunisia (1992), (41) Estimated from Morocco, (42) WB: Zaire (1986), (43) Openshaw (1997b) assumes 23.6% conversion efficiency, (44) Estimate based on Hosier et al. (1990), (45) Woods (1990), (46) Estimate based on Hosier (1985), Mungala and Openshaw (1984), and Kituyi et al. (1999)

Table 6. Agricultural Residues in Africa

Region	Residue Available Tg DM	Biofuels Tg	Burn in Fields Tg	Total Burned Tg (%)
Rainfed Drylands	15	<1	<1	˜1 (5)
Semi Arid Zone	70	19	21	40 (57)
Sub Humid Zone	39	9	10	19 (49)
Humid Zone	15	3	7	10 (67)
Eastern Highlands	27	13	6	19 (70)
South Africa (SugarCane)	7	3	4	7 (100)
Africa	173	47	48	95 (55)

Table 7. Woodfuels Use in Asia

Country	Total (Tg)	Per Cent Charcoal	Choice (kg/cap/day)	Other Estimates (kg/cap/day)	References
MIDDLE EAST					
Afghanistan	3.8	NA	0.57		1
Iran	0.9	NA	0.05		2
Iraq	2.4	NA	0.42		3
Pakistan	14.7	0.8	0.42	0.64,0.42	4,1,5
Turkey	17.8	NA	0.97	0.64,0.73	6,32,3
YemenAR	4.5	1.3	1.57		7
Other Countries	0.3	NA	0.00-0.06		3
FAR EAST					
Bangladesh	14.5	0	0.4	0.07,0.09,0.34,0.55	8,9,5,10,1
Bhutan	2.2	3	4.43		1
Brunei	0.2	NA	2.43		1
Myanmar	25.4	4	1.81	1.68,2.07	31,11,1
Indonesia	60.1	1.1	1.00	1.57,1.30,1.44,1.02,0.92	12,1,13,5,14,3
Japan	19.0	50	0.43		1
Cambodia	7.4	NA	2.83		1
KoreaN	3.1	NA	0.42		1
KoreaS	4.6	NA	0.31	0.23	1,15
Laos	4.3	NA	3.26		1
Malaysia	8.6	8	1.48		1
Mongolia	1.0	NA	1.45		1
Nepal	9.8	2	1.57	0.78,1.28,1.43,2.54	16,17,17,17,1
Philippines	29.9	5	1.52	1.0	1,5
Sri Lanka	6.4	1	1.06	1.27,0.93	1,18,19
Taiwan	1.3	NA	0.18		10
Thailand	28.3	53	1.50	2.26,0.7,1.22,2.7,6.3	33,20,21,5,22,10
Vietnam	25.8	7	1.18	0.41,0.69,0.81	23,24,5,25
WSamoa	0.1	0	1.25		26
PacificIslands	3.4	NA	0.7-2.1		1,27,28,29,30
Total	299.8				

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(1)Openshaw pc, (2) Fesharaki (1976), (3)De Montalembert and Clement, (1983), (4) Ebinger (1981), (5) Meyers and Leach (1989), (6) World Bank (WB): Turkey (1983), (7) WB: Yemen Arab Republic (1984), (8) Islam (1984), (9) WB: Bangladesh (1982), (10) Office of Technology Assessment (1991), (11)WB: Burma (1985), (12) Soesastro (1984), (13) WB: Indonesia (1981), (14) Di Marzo (1994), (15) Yager (1984), (16) WB: Nepal (1983), (17) Earl (1975), (18) Leach (1987), (19) WB: Sri Lanka (1982), (20) Moss&Morgan quoting Openshaw (1976), (21) WB: Thailand (1985), (22) Openshaw (1978), (23) WB: Vietnam (1994), (24) Tuan & Lefevre (1996), (25) England and Kammen (1993), (26) WB: Western Samoa (1985), (27) WB: Papua New Guinea (1982), (28) WB: Fiji (1983), (29) WB: Solomon Islands (1992), (30) WB: Vanuatu (1985), (31) Ministry of Forestry: Myanmar (1997), (32) Ileri and Gurer (1998),(33) Keith Openshaw, personal communication.

Table 8. Agricultural Residues in Asia

Region/Major Contributors	Residue Available Tg DM	Biofuels (%)	Burn in Fields (%)	Total Burned Tg (%)	Reference for Biofuel
FAR EAST[a]	364	16	43	216 (59)	
Indonesia	88	14	73	76 (86)	(1)
Thailand	57	14	53	38 (67)	(3)
Bangladesh	41	30	11	16 (41)	(8)
Vietnam	29	43	43	25 (86)	(2)
Philippines	30	14	65	23 (80)	(4)
Myanmar	29	13	49	18 (62)	(5)
MIDDLE EAST	117	21	21	49 (42)	
Afghanistan	7	54	16	5 (70)	(12)
Pakistan	51	15	19	16 (34)	(6)
Turkey	43	28	30	25 (58)	(7)
NEAR EAST	11	0	18	2 (18)	(9)
Total[a]	492	17	38	271 (55)	
China	632	47	1	300 (47)	(10)
India	347	25	23	168 (48)	(11)
Total Asia	1471	32	19	739 (50)	

Note: Dung (about 10 Tg/yr) is not included in the biofuels estimate. (a) Excluding China and India

(1) All Agroindustry including bagasse, rice husks and palm products; (2) World Bank: Vietnam (1994); (3) All Agroindustry and similar estimate in Meyers and Leach (1989); (4) All Agroindustry including bagasse, rice husks and palm products; (5) All Agroindustry including bagasse, rice husks and palm products; (6) Openshaw estimate, and similar estimate in Ebinger (1981); (7) World Bank: Turkey (1983); (8) based on Islam (1984); (9) Mostly used for fodder--see text; (10) Gao and Xu (1991); (11) Joshi et al. (1992); (12) Openshaw estimate

Table 9. Estimates of Biofuel Consumption in China (MTCE)[a]

Source and Estimate Year[b]	Wood	Crop Residue	Dung
Gao and Xu 1986[c]	141	136	10
ESMAP 1979[d]	104	114	-
ESMAP 1989[d]	138	136	-
Qui 1987[e]	132	150	
OTA 1987[f]	168	-	-
Meyers and Leach 1989[g]	109	-	-
Barnard and Kristoferson 1985[h]	-	120	-

(a) 1 MTCE = 29.3 PJ (Gao and Xu, 1991) (b) All estimates are per year indicated. (c) Gao and Xu, 1991 (d) ESMAP, 1996, (e) Qui, 1992, (f) Office of Technology Assessment (OTA), 1991, (g) Meyers and Leach, 1989, (h) Barnard and Kristoferson, 1985

Table 10. Woodfuel, Residue, and Dung Domestic Fuels in China (Tg DM/yr)

Province	Woodfuel	Agricultural Residue	Dung
Xinjiang	2.36	5.11	6.72
Xizang	-	0.44	0.98
Qinghai	0.21	0.81	2.01
Gansu	1.21	4.66	10.08
Yunnan	22.08	7.85	-
Sichuan	34.62	28.83	-
Heilongjiang	4.52	7.22	-
Nei Monggol	8.60	6.99	-
Ningxia	0.29	1.48	-
Jilin	3.65	5.00	-
Liaoning	5.74	11.56	-
Guangxi	15.05	10.06	-
Guizhou	20.37	6.04	-
Guangdong	13.03	14.04	-
Hunan	19.84	19.79	-
Hubei	11.48	16.36	-
Shaanxi	10.50	7.57	-
Shanxi	2.83	5.34	-
Henan	14.03	21.30	-
Jiangxi	15.47	12.18	-
Fujian	13.34	5.97	-
Zhejiang	15.55	12.36	-
Anhui	7.55	12.18	-
Jiangsu	3.20	22.28	-
Shandong	15.70	27.18	-
Hebei	2.64	16.38	-
Beijing	-	2.12	-
Tianjin	-	1.50	-
Shanghai	-	1.85	-
Totals	263.85	294.48	19.79

Taken from Gao and Xu (1991) and scaled to 1985 using populations from *FAO*, 1986a. See text.

Table 11. Woodfuel, Residue, and Dung Domestic Fuels in India (Tg DM/yr)

State	Woodfuel	Agricultural Residue	Dung
Andhra Pradesh	20.11	16.12	8.23
Assam	11.87	2.34	1.21
Bihar	29.55	6.76	7.11
Gujarat	7.45	2.60	1.99
Haryana	1.47	1.30	2.25
Himachal Pradesh	1.56	0.00	0.26
Jammu & Kashmir	1.85	0.71	0.61
Karnataka	9.19	6.76	2.25
Kerala	6.41	0.87	1.04
Madhya Pradesh	28.25	4.94	5.37
Maharashtra	17.33	6.59	2.51
Manipur	0.78	0.17	0.09
Meghalaya	0.87	0.17	0.09
Nagaland	0.61	0.09	0.09
Orissa	22.53	6.59	3.73
Punjab	1.65	1.56	2.60
Rajasthan	8.49	2.43	6.76
Tamil Nadu	15.51	12.05	6.50
Tripura	1.39	0.26	0.17
Uttar Pradesh	14.39	4.85	32.24
West Bengal	17.59	9.10	7.80
Arunachal Pradesh	0.43	0.09	0.09
Mizoram	0.26	0.09	0.00
Sikkim	0.26	0.09	0.00
Totals	219.82	86.51	93.00

Derived from Joshi et al. (1992). See text.

Table 12. BIOMASS FUEL USE IN LATIN AMERICA (PJ fuel/yr)(1985)[a,b]

Country	Wood	Chrcl	Ag Res[c]	Dung	References[d]
ANDEAN PLUS					
Colombia	196.7	0.0	26.6	0.0	1,1
Peru	120.2	5.0	20.2	24.7	2,2,2,3
Chile	65.5	0.0	0.0	0.0	4
Ecuador	29.6	0.1	15.1	0.0	5,5,6
Bolivia	22.7	2.5	5.2	7.1	7,8,6,7
Paraguay	57.7	4.6	3.7	0.0	9,9,10,10
Argentina	36.0	11.4	28.6	0.0	4,4,6
Uruguay	23.9	0.0	1.4	0.0	4,6
CEN. AMERICA					
Guatemala	111.8	0.8	19.5	0.0	11,11,6
El Salvador	55.0	0.0	4.3	0.0	12,12
Honduras	50.5	1.3	4.1	0.0	13,13,13
Nicaragua	30.0	4.2	7.3	0.0	14,14,6
Costa Rica	20.9	0.5	7.3	0.0	15,15,6
Panama	14.0	0.0	7.6	0.0	12,12
Belize	1.0	0.0	2.5	0.0	16,6
CARIBBEAN					
Cuba	57.9	0.0	189.5	0.0	4,6
Haiti	41.4	3.9	7.8	0.0	17,17,6
Dominican Rep	11.2	20.9	26.5	0.0	18,18,6
Jamaica	1.6	18.2	6.1	0.0	19,19,6
Other	0.4	1.6	2.6	0.0	20,20,6
NORTH COAST					
Venezuela	17.0	0.0	14.8	0.0	21,6
Guyana	5.0	0.0	9.2	0.0	4,6
Surinam	1.3	0.0	0.3	0.0	4,6
Fr. Guyana	0.3	0.0	0.0	0.0	22
BRAZIL	1070.0	565.0	639.2	0.0	23,23,6
MEXICO	293.0	0.0	98.4	0.0	24,6
TOTALS	2334.6	640.0	1149.7	31.8	

(a) In energy units for comparison of different biofuels (b) No estimates for residue burned in the fields included (c) Mainly bagasse as agroindustrial fuel (d) Only given for nonzero values which have been adjusted to year 1985

(1) World Bank: Colombia (1986), (2) World Bank: Peru (1984), (3) World Bank: Peru (1990), (4) OLADE (1981), (5) World Bank: Ecuador (1994), (6) Bagasse in Agroindustry, (7) World Bank: Bolivia (1994), (8) World Bank: Bolivia (1983), (9)Division de Programacion Energetica (1986), (10) World Bank: Paraguay (1984), (11) World Bank: Guatemala (1993), (12) Bogach, (1990), (13) World Bank: Honduras (1987), (14) van Buren (1990), (15) World Bank: Costa Rica (1984), (16) Use woodfuel per capita of Colombia, (17) World Bank: Haiti (1991), (18) World Bank: Dominican Republic (1991), (19) World Bank: Jamaica (1985), (20) Grenada: OLADE (1981); St. Lucia, World Bank: St. Lucia (1984); St Vincent and the Grenadines, World Bank: St Vincent and the Grenadines (1984); Trinidad and Tobago, World Bank: Trinidad and Tobago (1985), (21) Rural wood use based on Ecuador, (22) Wood use based on Surinam per capita, (23) Meyers and Leach (1989), (24) Martinez (1992)

Table 13. Biomass Combustion (Tg DM 1985)

	Burn in Fields	Biofuel				Total DM Burned (Residue)[a]
		Residue	Dung	Woodfuel	Total Fuel	
Africa	49	47	11	354	412	461 (96)
Asia	274	465	123	784	1372	1646 (739)
India	81	87	93	220	400	481 (168)
China	6	294	20	264	578	584 (300)
Latin America	85	85	2	186	273	358 (170)
Brazil	42	47	-	102	149	191 (89)
Totals Devlping World	408	597	136	1324	2057	2465 (1005)
N. America, CIS, W. Europe	36 (US)	-	-	388	388	424 (36)
Australia	7	-	-	2	2	9 (7)
Totals	451	597	136	1714	2447	2898 (1048)

(a) The last column gives the total dry matter burned, including woodfuels, dung, residue burned as fuel and residue burned in fields. The number in parenthesis is the total amount of residue burned.

Table 14. Agricultural Residue Burned in the Fields (Tg DM 1985)

	Total Residue Available	Rice Straw	Barbojo	Other[a]	Total Available Residue BIF (%)
Africa	173	4	12	33	49 (28)
Asia	1471	170	29	75	274 (18)
India	347	48	7	26	81 (23)
China	632	3	1	2	6 (1)
Latin America	360	-	77	8	85 (23)
Brazil	152	-	42	-	42 (28)
Totals Devlping World	2004	174	118	116	408 (20)

(a) Includes other cereal residues, cotton residues, coffee processing residues, (see text)

Table 15. Biofuels Combustion-Estimates (PJ)

Estimate Year	Streets and Waldhoff (1990)	Woods and Hall (1990)	This work (1985)
Total Asia	22,000	29,695	20,605
China	9800	9300	8483
India	7254	8543	6130
Indonesia	1190	2655	1138
Vietnam	537	896	589
Thailand	397	-	559
Philippines	309	856	532
Myanmar	272	550	460
Turkey	-	605	447
Pakistan	724	1246	434
Bangladesh	499	1523	438
Japan	88	6	304
Total Africa	-	9,160	6,443
Nigeria	-	2,225	932
Ethiopia	-	540	698
Tanzania	-	925	497
Sudan	-	843	564
Kenya	-	404	395
Total Latin America	-	3726	4156
Brazil	-	1604	2274
Mexico	-	404	391
Total Developing World	-	42,631	31,203

Table 16. Biomass Combustion Estimated for 1995 (Tg DM)

	Burning in Fields	Agr. Residues + Dung (Biofuel)	Fuel Wood + Charcoal	Total Biomass Fuel
Africa				
1985	49	58	354	412
1995	57	72	464	536
Change	+16%	+24%	+31%	+30%
Asia				
1985	274	588	784	1372
1995	348	678	930	1608
Change	+27%	+15%	+19%	+17%
Latin America				
1985	85	87	186	273
1995	91	107	221	328
Change	+7%	+23%	+19%	+20%
Totals				
1985	408	733	1324	2057
1995	496	857	1615	2472
Change	+22%	+17%	+22%	+20%

Table 17. Emissions From Biofuels Combustion (Tg pollutant/yr)

Sources	Biofuels (Tg DM)	CO_2	CO	CH_4	NO_x*
Africa					
Fuelwood	295	433	21	1.33	0.30
Charcoal	10	27	2	0.08	0.04
Crop Res	47	56	4	0.22	0.03
Dung	11	11	1	0.03	0.03
Total	363	527	28	1.66	0.40
Asia					
Fuelwood	753	1105	53	3.39	0.75
Charcoal	9	25	2	0.07	0.03
Crop Res	465	554	40	2.14	0.33
Dung	123	124	7	0.33	0.30
Total	1350	1808	102	5.93	1.41
Latin America					
Fuelwood	146	214	10	0.66	0.08
Charcoal	13	36	3	0.10	0.05
Crop Res	85	101	7	0.39	0.06
Dung	2	2	-	0.01	0.01
Total	246	353	20	1.16	0.20
Total Developing World	1959	2688	150	8.75	2.01

*Units are Tg N/yr for NO_x

Table 18. Emissions From Charcoal Production (Tg pollutant/yr)

Sources	Charcoal produced (Tg)	CO_2	CO	CH_4	NO_x*
Africa					
Earth Mound Kiln[a]	9.6	15.3	2.4	0.37	0.0007
Asia					
Mix of Kilns[b]	9.3[d]	13.0	1.2	0.17	0.0009[c]
Latin America					
Brazil (Commercial)					
Brick Beehive[b]	11.8	11.4	1.9	0.38	0.0011[c]
Other					
IPCC[c]	0.9	1.43[a]	0.2	0.03	0.0001
Total	31.6	41.17	5.7	0.95	0.0028

* Units are Tg N/yr for NO_x (a) Emission factors from Brocard et al, (1998). (b) Emission factors from Smith et al. (1999). (c) IPCC emission factors from Smith et al. (1999). (d) Charcoal production at individual country efficiency (˜ 25% average) and includes 0.5 Tg charcoal in India

Table 19. Emissions from Field Burning of Residues (Tg pollutant/yr)

	CO_2	CO	CH_4	NO_x*	TPM
Africa	55	2.5	0.11	0.02	0.20
Asia	310	14.0	0.60	0.14	1.15
India	91	4.1	0.18	0.04	0.34
China	7	0.3	0.01	0.00	0.02
Latin America	96	4.3	0.19	0.04	0.36
Brazil	48	2.1	0.09	0.02	0.18
N. America, CIS, W. Europe,Australia	49	2.2	0.09	0.02	0.18
Totals	510	23.0	0.99	0.22	1.89

*Units are Tg N/yr for NO_x

Table 20. Global Emission Estimates (1985)

	CO_2	CO	CH_4	NO_x
Fossil Fuel, Industry	5.3 (a)	300 - 400 (b)	75 - 110 (c)	21 (c)
Biomass Fuel*	0.74	150	9	2.0
Charcoal Production*	-	6	1	-
Field Residue Burning**	0.14	23	1	0.2
Biomass Burning	2.3 (c)	300 - 770 (c)	23 - 55 (c)	3 - 13 (c)
Total Sources		2100 - 2800(c)	500 - 600 (c)	44 - 52 (c)

Units are Pg C/yr for CO_2, Tg CO/yr, Tg CH_4/yr, and Tg N/yr for NO Estimates are given for 1985 for fossil fuel and industry.

* From developing world only. ** Also includes BIF of Developed World (a) Marland et al. (2001), (b) Olivier et al. (1999), Duncan et al. (2002), (c) IPCC, (2001)

Table 21. Comparison of Biofuel and Fossil Fuel Combustion (tg C 1985)

	Biofuel			Total Biofuel	Total Fossil Fuel (a)
	Residue	Dung	Woodfuel		
Africa	19	4	159	182	168
Asia	186	43	353	582	1286
India	35	33	99	167	133
China	118	7	119	244	531
Latin America	34	1	84	119	239
Brazil	19	-	46	65	48
Totals Devlping World	239	48	596	883	1693
N. America, CIS, W. Europe	-	-	175	175	2977
Australia	-	-	1	1	61
Totals	239	48	772	1059	5405 (b)

(a) Carbon Dioxide Information Analysis Center (CDIAC) website (b) CDIAC global total also includes bunker fuels, asphalt oxidation, etc (Tom Boden, personal communication).

Table 22. Emission Factors[a] for Biofuels Combustion in Simple Cookstoves(gm pollutant/kg dry matter)

Sources (% C)	CO_2	CO	CH_4	NO_x*	TSP
FUELWOOD					
Zhang et al.[i]	1410-1630	24-123	0.54-19.9	0.12-2.78	1.51-8.73
(44.5-45.6)	(1520)	(69.2)	(5.06)	(1.19)	(3.82)
Smith et al.[c]	1260-1536	60-139	3.4-11	-	8-25
(41.8-45.5)	(1395)	(66.5)	(3.93)	(0.89)	(5.17)
Brocard et al.[h]	1467	70	2	0.7	-
(46)					
Marufu[e]	1610/1486	100/90	-	0.52	-
(50/45)					
Bertschi et al.[f]	1525	96	10.6	0.95	-
(48)					
Early Reports**	1460-1480	39-106	-	-	2.9-15.0
Choice Dev.Wrld	1467	70	4.5[b]	1.0[b]	4.5[b]
CHARCOAL					
Zhang et al.[i]	2450	275	-	-	-
Smith et al.[d]	2740	230	8	-	-
Bertschi et al.[f]	2402	134	6.9	0.7	-
Lazarus***	2780	264	-	-	-
Choice Dev. World	2740	230	8	3.9	
DUNG					
Smith et al.[c]	974-1065	32-60	3.3-17.0	-	0.54-2.03
(33.4)	(1010)	(60)	(17)	-	(1.22)
Marufu[j]	1610/1103	84/58	-	-	-
(50/33.4)					
Choice Dev.World	1010	60	2.7[e]	2.4[e]	1.22
CROP RESIDUE (MIX)					
Zhang et al.[i]	834-1370	24-223	.004-15.9	.004-2.2	1.12-29.0
(34.8-40.3)	(1130)	(86)	(4.6)	(0.70)	(8.1)
Smith et al.[c]	983-1302	55-101	3.8-25	-	0.63-14.9
(38.1-42.1)	(1192)	-	-	-	(1.08)
Marufu[j]	1720/1200	63/44	-	1.7	-
(50/34.8)					
Smith[g]	1220	110	-	-	35

Choice Dev.World	1192	86	4.6	0.7	8.1

* Units are gms N for NOx ** Mainly Butcher, 1984 as summarized in Lazarus and Diallo (1992) and Smith : Global Review (1987) ***Islam 1987 in Lazarus and Diallo (1992) (a) First line gives range of emission factors and second line is the mean. (b) Mean Smith et al. (2000) and Zhang et al. (2000) (c) Smith et al. (2000) (d) Smith et al. (1993) (e) '/' is used to give the recalculated value of CO_2 if Marufu had used a more realistic C-content of the fuel (f) Bertschi et al. (2002) assumed all burned carbon was volatilized (g) Smith (1987), (h) Brocard et al. (1998), (i) Zhang et al. (2000), (j) Marufu (1999).

Table 23. Emission Factors for Charcoal Production (gm pollutant/kg charcoal produced)

Sources	CO_2	CO	CH_4	NO_x*
Earth Mound Kilns (Africa)				
Smith[a]	1140	226	28	--
Brocard[b]	1593	254	39	0.073
Pennise et al.[c]	1058-3027	143-333	32.2-61.7	-
Brick Beehive Kiln (Brazil Commercial)				
Smith[a]	966	162	32	--
Pennise et al.[c]	543-1533	162-373	36.5-56.8	-
Mix of Kilns (Asia)				
Smith[a]	1403	133	18	--
World Average				
IPCC[a]	--	210	30	0.091

* Units are gms N for NO_x (a) Smith et al. 1999. (b) Brocard et al. 1998. (c) Pennise et al. 2001.

Table 24. Emission Factors for Residue BIF (gm pollutant/kg DM)

Sources (Residue)	CO_2	CO	CH_4	NO_x*	TPM
Ezcurra et al. (1996)					
Cereal[b]	1032 - 1283	-	-	0.69 - 0.77	16.0 - 26.0
Nguyen et al. (1994)					
Rice[c]					
Dry Season	977	79	4.1	-	-
Wet Season	831	143	12.3	-	-
Jenkins and Turn (1994)					
Rice[c]	1072	29	0.7	0.62	3.2
& Cereals[d]	1091 - 1201	35 - 92	1.6 - 2.3	0.32 - 0.55	5.4 - 7.2
IPCC[g]					
Sugar Cane[e]	-	54 - 90	2.89 - 5.37	0.21 - 0.66	-
Choice	1132	51	2.2	0.52	4.2
Andreae and Merlet. (2000)					
Savannah[f]	1613	65	2.3	1.82	8.3

*Sources differ in definition of NO_x; These units are in gms N for NO_x (b) 10% Moisture Content wet basis (MC), (c) 8.5% MC, (d) 6.9-8.6% MC, (e) 15% MC, (f)MC not specified (g) from Scholes et al. (1995).

Figure 1: Residue Use in Africa (%)

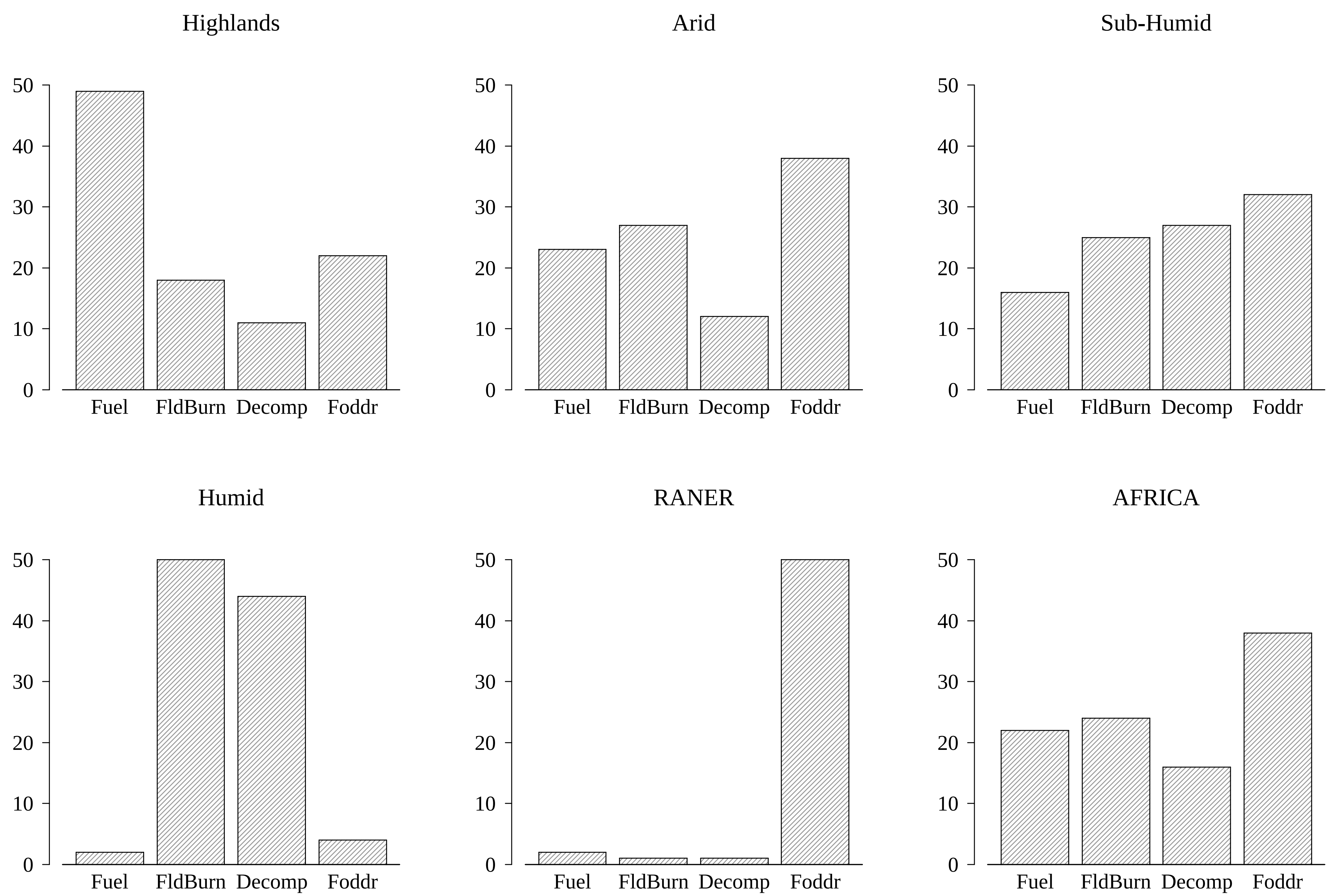

FIGURE 2: Residue in Asia (Tg DM)

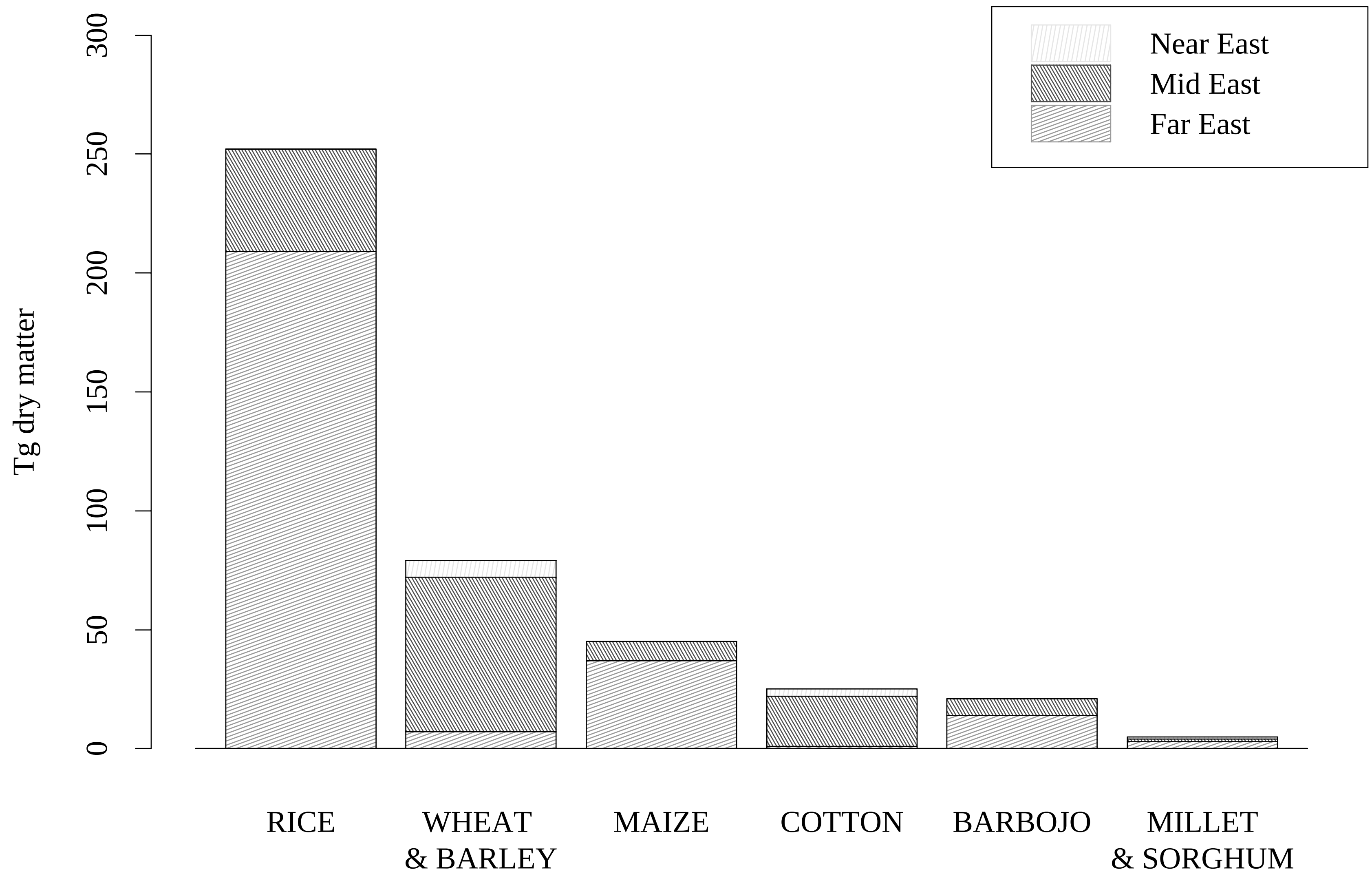

FIGURE 3 Woodfuel Use in Developing World (TG DM)

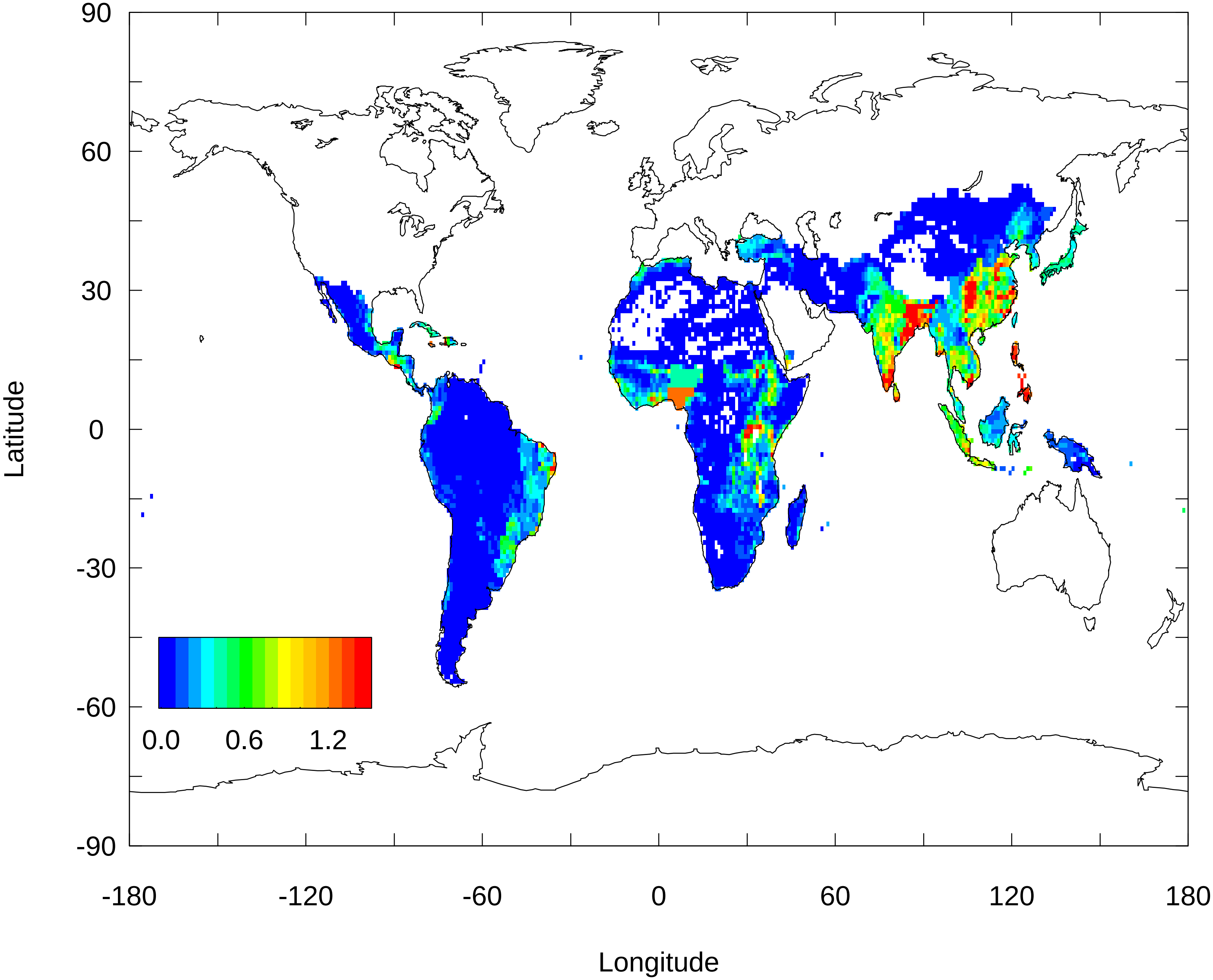

FIGURE 4: Residue & Dung Biofuels in Developing World (TG DM

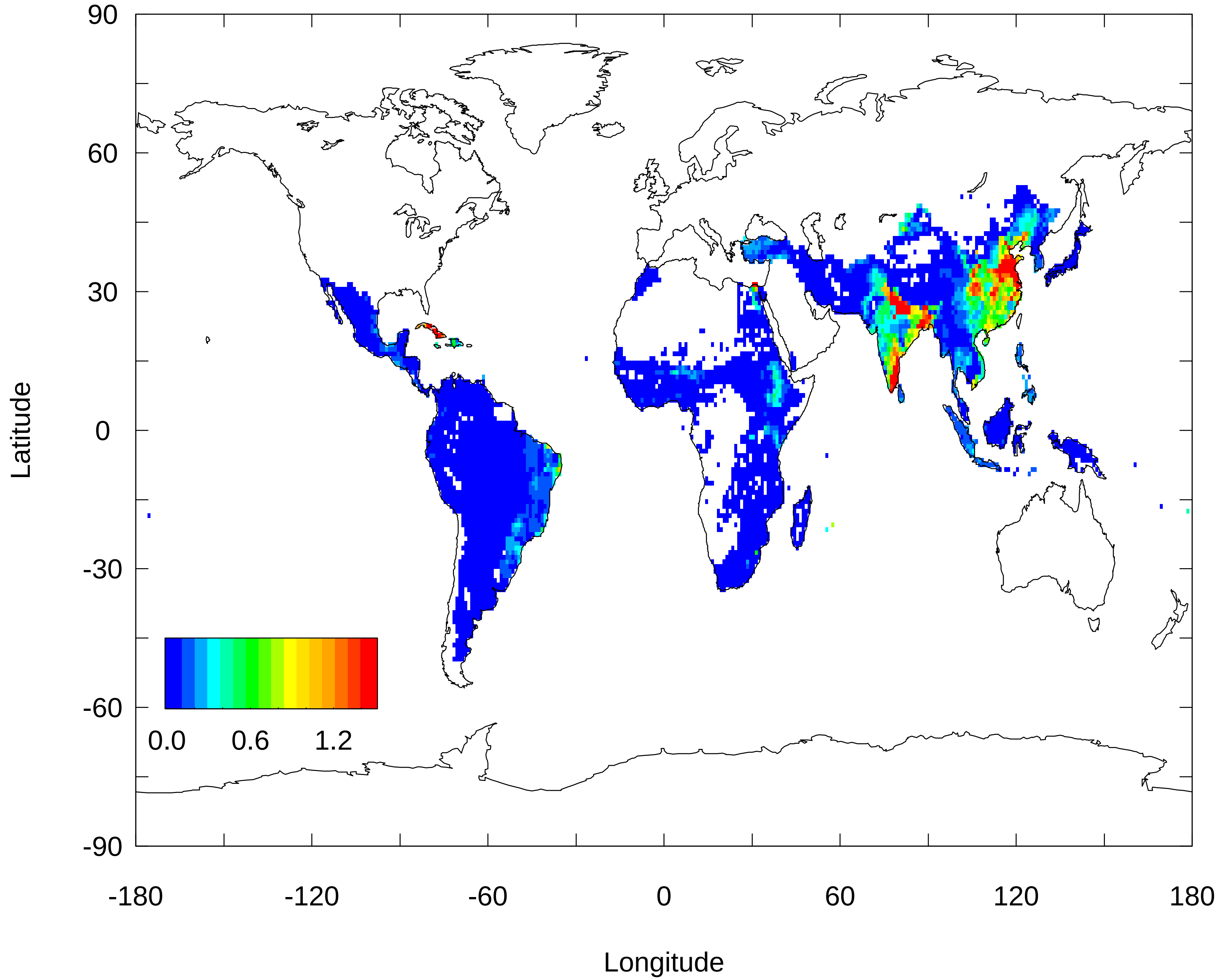

FIGURE 5: Burning in Fields in Developing World (tg DM)