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Global biofuel use, 1850–2000

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[1] This paper presents annual, country-level estimates of biofuel use for the period 1850–2000. We estimate that global biofuel consumption rose from about 1000 Tg in 1850 to 2460 Tg in 2000, an increase of 140%. In the late 19th century, biofuel consumption in North America was very high, ~220–250 Tg/yr, because widespread land clearing supplied plentiful fuelwood. At that time biofuel use in Western Europe was lower, ~180–200 Tg/yr. As fossil fuels became available, biofuel use in the developed world fell. Compensating changes in other parts of the world, however, caused global consumption to remain remarkably stable between 1850 and 1950 at ~1200 ± 200 Tg/yr. It was only after World War II that biofuel use began to increase more rapidly in response to population growth in the developing world. Between 1950 and 2000, biofuel use in Africa, South Asia, and Southeast Asia grew by 170%, 160%, and 130%, respectively.

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1. Introduction

[2] In this paper we develop estimates of annual biofuel consumption from 1850–2000 at national level. The primary purpose of this work, when combined with similar estimates of fossil-fuel use documented in a companion paper [*Bond et al.*, 2007], is to estimate historical emissions of carbonaceous aerosols. Biofuels (fuelwood, agricultural residues, charcoal, and dung) were the staples of human energy needs until coal became available in the developed world in the late 19th century, and biofuels continue to fulfill their traditional roles in many parts of the developing world today. Because biofuel combustion in household stoves and small-scale industrial facilities has high emission rates of carbonaceous aerosols, on the order of 0.1–1.5 g kg^{-1} of black carbon and 0.3–8 g kg^{-1} of organic carbon [*Bond et al.*, 2004], it is critical to assess the historical contribution of biofuel usage to aerosol emissions and human-induced climate change.

[3] Historical trends in biofuel use are closely linked to other indicators of human activity: agricultural production and the demand for food [*Hoogwijk et al.*, 2003], patterns of land use [*Houghton et al.*, 1983; *Ramankutty and Foley*, 1998, 1999; *Houghton*, 1999; *Klein Goldewijk*, 2001; *Waisanen and Bliss*, 2002], and deforestation rates [*Achard et al.*, 2002]. However, previous historical inventories of atmospheric emissions either ignored biofuel consumption or treated it by simply extrapolating present-day per capita consumption rates using population trends [*Stern and Kaufmann*, 1996; *Andres et al.*, 1999; *Lefohn et al.*, 1999; *van Aardenne et al.*, 2001; *Novakov et al.*, 2003; *Junker and Liousse*, 2006].

[4] Hall and coworkers [*Hall*, 1991; *Hall et al.*, 1994] were the first to attempt a systematic compilation of the amounts of biofuel used in various countries. Their estimate of global consumption was 4106 Tg for the year 1987 [*Hall et al.*, 1994]. *Ludwig et al.* [2003] estimated residential consumption of biofuels in 1995 to be 3199 Tg in a study of the contribution of biofuels to atmospheric pollutants. The first detailed inventory of global biofuel combustion was compiled by *Yevich and Logan* [2003]. Their estimate of the total amount of biofuel burned in 1985 was 2447 Tg, consisting of 1714 Tg of fuelwood, 597 Tg of agricultural residues, and 136 Tg of dung. These previous biofuel studies did not investigate how consumption has changed over time. *Ito and Penner* [2005] developed trends of biofuel consumption from 1870–2000 in the context of estimating carbonaceous aerosol emission. Several organizations compile statistical data on energy and fuel-use trends that include biofuels, such as the *International Energy Agency* [2004a, 2004b] (IEA) and the *Food and Agriculture Organization* [1997a] (FAO); however, these studies are only reliable for recent years, do not always distinguish biofuel use by sector or fuel type, and are not inclusive of all countries in the world. While data from these sources are helpful in anchoring extrapolations back in time, they must be used selectively and with caution.

[5] Despite the acknowledged shortcomings of previous treatments of historical biofuel use, a number of historical air quality and climate simulations have been conducted in recent years [*Lamarque et al.*, 2005; *Stier et al.*, 2006; *Dentener et al.*, 2006, *Tsigaridis et al.*, 2006; *Schulz et al.*, 2006]. There is clearly a need for a more realistic assessment of biofuel use since the dawn of the industrial

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revolution. This work presents the first systematic quantification of historical trends in global biofuel consumption from 1850–2000. For the developed world, particularly the United States and western Europe, there is some information on historical industrial activity and fuelwood consumption. For most countries, however, including the entire developing world, there is almost no historical information, and new methodologies had to be created to estimate trends back to 1850, anchored wherever possible to recent, documented consumption amounts.

2. Methodology

[6] Few biofuel consumption data are available prior to the last three decades, so wherever observational data were lacking, we calculated consumption by combining estimates of per capita biofuel use with population data, taking into account country-specific factors that might have caused per capita consumption rates to change over time. We began by developing annual, country-level population estimates from 1850–2000, including urban and rural population splits.

2.1. Population

[7] The United Nations supplies annual country-level population data since 1950 [*United Nations*, 2000], but other sources of pre-1950 data are less comprehensive. Since *Maddison* [2003] provides the most complete data set for the 19th century, we used it as the foundation for our historical population estimates. When Maddison's data were unavailable or significantly disagreed with UN data for overlapping periods, we consulted *Lahmeyer* [2002] and *Mitchell* [1998a, 1998b, 1998c]. We used these data sources to construct annual population trends for all countries back to 1850, interpolating for missing years by assuming constant growth rates between known values. Post-1950 urban/rural population splits were taken directly from the UN data [*United Nations*, 2000]. We estimated pre-1950 urban populations by assuming that the urban population for a country is proportional to the populations of its largest towns and cities, as specified by Lahmeyer. We combined all Lahmeyer data for a given country and year, so our values reflect an average over all urban areas in a country. Fractional urban population values were applied to the total population to generate historical urban populations. Rural populations were determined by subtracting urban from total.

2.2. Residential Biofuel Consumption and Regional Considerations

[8] Residential biofuel consumption from 1850–2000 was calculated, by country, on the basis of: (1) current residential fuel-use patterns, (2) qualitative and quantitative information about national biofuel use, and (3) historical urban/rural population trends. We assigned modern per capita consumption rates to each country on the basis of current activity data and extrapolated back to 1850, taking into consideration fuelwood depletion (see section 2.2.1), urbanization, and fossil-fuel substitution. Residential biofuel consumption was calculated for each country as follows:

$$RB_{c,t,x,y} = RF_{c,t,x}{}^{*}fB_{c,t,x,y}{}^{*}P_{c,t,x}, \quad , \tag{1}$$

where c = country; t = year, 1850–2000; x = urban/rural segment of population; y = biofuel type (fuelwood, charcoal, crop residue, dung); RB = residential sector biofuel consumption; RF = per capita residential fuel consumption; fB = biofuel fraction of RF; and P = population.

[9] Transitions between known per capita biofuel usage rates in modern times and assumed historical per capita biofuel rates were constructed using a transformed-normal curve (s-curve) transition methodology, as described by *Streets et al.* [2004]. The following transformed-normal distribution function was used to interpolate biofuel usage:

$$RB(m)_{c,t,x,y} = RB(h)_{c,t,x,y} e^{\left(-T^2/2s^2\right)} \quad , \tag{2}$$

where $RB(m)$ = biofuel usage in the "modern" period; $RB(h)$ = biofuel usage in the "historical" period; T = intervening time period in years; and s = shape parameter for the curve.

[10] The use of such diffusion curves to simulate the dynamics of technology transitions is discussed by *Grübler et al.* [1999] and *Geroski* [2000]. In the absence of published information about the onset of fossil fuels in a given country, we assumed that biofuel consumption started to decrease as fossil-fuel use began to increase, and we determined the transition year and functional shape by examining the period when fossil-fuel use began to increase, as documented in the CDIAC database [*Marland et al.*, 2006].

[11] Residential biofuels were subdivided into four categories, fuelwood, charcoal, agricultural residues, and dung, on the basis of current fuel splits that we adjusted backward in time, reflecting country-specific pressures on natural and human resources. We considered wood to be the preferred fuel for most countries with wood availability, and we assumed that dung and crop residues met any shortfall between total energy needs determined from the per capita calculations and reported fuelwood usage. Crop residues are generally not preferred over fuelwood because of their low combustion efficiency and the fact that they can be used as fertilizer or animal food. For countries that currently prefer crop residues and dung use despite fuelwood abundance, we researched the factors contributing to this preference to determine historical usage. Charcoal usage was taken from international statistics for the modern period and extrapolated back in time using national GDP data and historical usage estimates from *Maddison* [2003].

[12] We used statistics on local populations that continue to use biofuels to represent historical biofuel usage in the absence of conflicting pressures such as fuelwood depletion. We were thus able to generate country-specific estimates of per capita biofuel consumption that captured cultural practices and region-specific energy needs. We assumed that both rural and urban per capita biofuel consumption rates had country-specific maxima in 1850 that declined toward modern rates under the influences of population density, fossil-fuel availability, biofuel availability, etc.

2.2.1. Africa

[13] In Africa, biofuel use has steadily increased over time. Most parts of Africa are currently dependent on urban

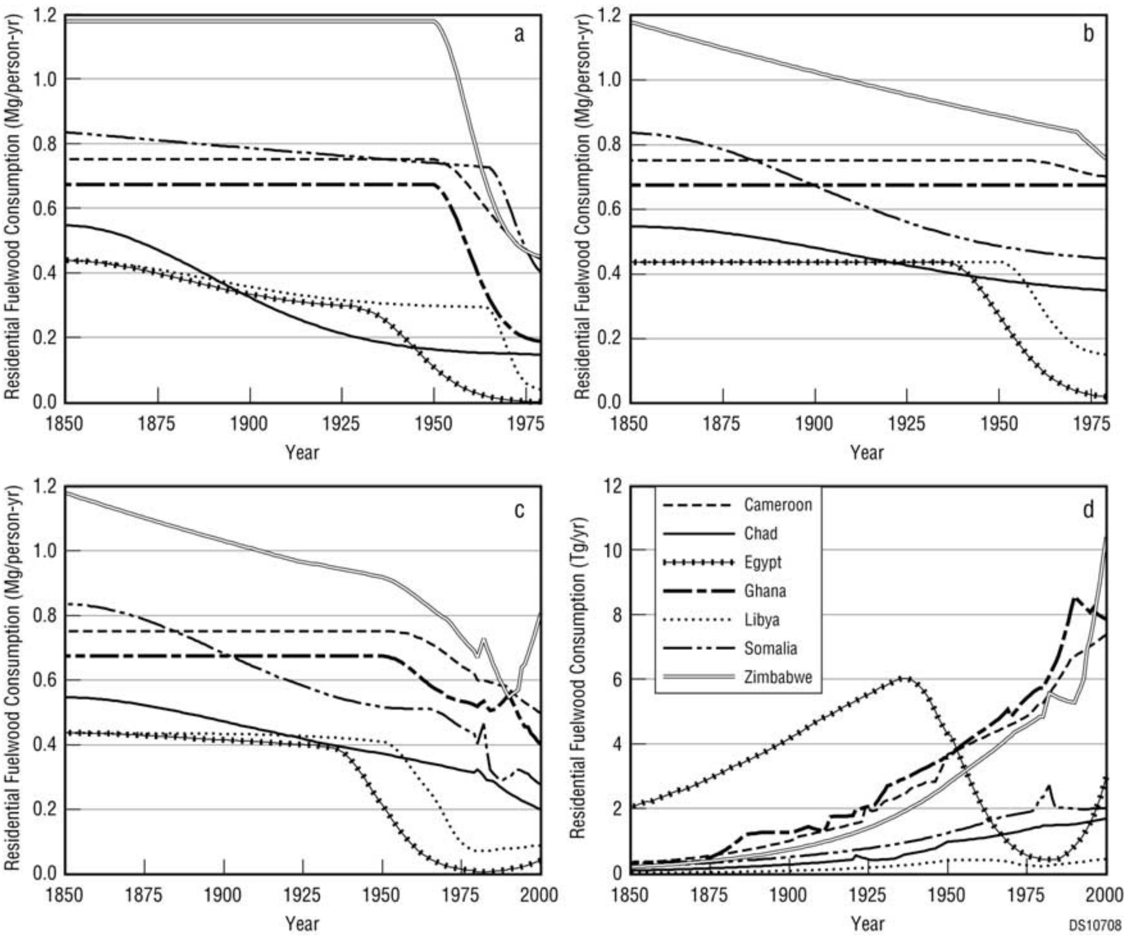

Figure 1. Trends in (a) urban and (b) rural annual per capita residential fuelwood consumption rates for selected African countries, 1850–1979. (c) Full per capita trends are formed by combining data from Figures 1a and 1b with FAO data from 1980–2000. (d) The complete residential fuelwood combustion trends for the same countries are obtained by combining urban and rural per capita usage rates with urban and rural historical population data.

and rural fuelwood, but data for past years are not readily available. For modern usage of residential biofuels, we used sources such as the FAO Role of Wood Energy Development Programme "best estimates" database for 1980–2000 (S. Amous, The role of wood energy in Africa, 1999, available from the Food and Agriculture Organization at http://www.fao.org/docrep/x2740e/x2740e00.htm) (hereinafter referred to as FAO website, 1999), World Bank country reports under the Energy Sector Management Assistance Program (individually listed in the auxiliary material[1]), a survey by *Brocard et al.* [1998], and selected country-specific studies. To estimate historical African biofuel consumption, we subdivided countries into four categories: rural with fuelwood depletion, rural with no depletion, urban with depletion, and urban with no depletion. Fuelwood depletion is a major concern in such countries as Burkina Faso, Burundi, Ivory Coast, and Nigeria [*Schulte-Bisping et al.*, 1999; *Ogunkunle and Oladele*, 2004]. From the literature, we identified which countries are presently suffering the effects of fuelwood depletion and in which year depletion began (see auxiliary material Table S1). Auxiliary material Tables S1–S4 are examples of the calculations made for many world regions.

[14] In countries with no apparent depletion, we assumed that rural per capita biofuel consumption in 1850 was equal to current rural per capita consumption and that urban per capita values were equal to rural levels in 1850. These values were then trended forward in time to connect with the modern data. In countries with present-day fuelwood shortages, we assumed that 1850 per capita usage was equal to that in neighboring, nondepleted countries with similar natural resources. We then assumed that fuelwood use decreased throughout the period and that the use of crop residues as fuel was proportional to the fuelwood deficit, as defined in World Bank country reports. Figure 1 presents some examples of the trends obtained by this method. Auxiliary material Tables S1–S3 present detailed data on

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gb/2006gb002836. Other auxiliary material files are in the HTML.

urban and rural per capita fuelwood consumption rates and total fuelwood consumption for each African country. A similar methodology was used for agricultural residues [*Koopmans and Koppejan*, 1997].

[15] We assumed that dung was used to supplement fuelwood only in Ethiopia, since dung use is discouraged in other countries for social and economic reasons [*World Bank*, 1984a]. Charcoal is almost exclusively an urban African fuel except in Sudan [*World Bank*, 1983a]. Higher-income urban dwellers are able to afford charcoal, although above a certain income level fossil fuels become the preferred energy source. Because charcoal consumption is minor relative to fuelwood and urban populations in Africa are low at the beginning of the study period, we assumed a constant, low-level per capita usage rate in countries without depletion at the beginning of the study period.

2.2.2. South Asia

[16] South Asia utilizes one of the most diverse biofuel mixes in the world. High population density causes severe pressure on all energy resources, and readily available fuels such as agricultural residues and dung ease the demand for fuelwood [*Sinha et al.*, 1998; *Mahapatra and Mitchell*, 1999]. The country with the most severe deforestation is Nepal [*World Bank*, 1983b]. In rural South Asia, biofuels account for over 90% of residential fuel consumption in most countries [*Food and Agriculture Organization*, 1997a; *Viswanathan and Kumar*, 2005]. We assumed that rural per capita fuel consumption in these areas has remained constant over time. We also assumed that the relative mix of biofuels in most countries has remained constant in the absence of contrary data. The major exception is Nepal, where we estimate that the share of fuelwood in total biofuels dropped from 95% in 1850 to its current level of 74% [*World Bank*, 1983b; *Food and Agriculture Organization*, 1997b]. Additionally, recent increases in the percentage of fuelwood consumed relative to other biofuels have been observed in India and Bangladesh (from 54% to 59% in the period 1978–2000), which can be attributed to urbanization relieving the pressure on rural forests. As people in urban areas become increasingly wealthy, they switch away from fuelwood to more-desirable fossil fuels. This relieves the pressure on supplies of fuelwood and makes more fuelwood available for rural households that cannot afford fossil fuels (or do not have access to them). Fuelwood is a more desirable biofuel option than crop residues or animal waste for rural households, and therefore they switch to fuelwood, increasing the fractional share of fuelwood in the biofuel mix [*Food and Agriculture Organization*, 1997a; *Islam*, 1984]. Fuelwood use as a fraction of total energy needs increased for rural populations from 68% to 78% during 1978–2000 in India and from 10% to 13% in Bangladesh.

[17] In urban areas, there has been significant substitution of fossil fuels for biofuels in recent years [*Misra et al.*, 1995]. India was the first country in the region to begin residential use of fossil fuels around the turn of the century. The rate of substitution began to increase just before the partitioning of India in 1947, and the fraction of traditional fuels dropped from 90% to 33% [*Tata Energy Research Institute*, 2000; *Government of India*, 1981]. Fuelwood made up the bulk of this consumption throughout the period, with charcoal and dung contributing a small but growing fraction. Per capita total energy consumption has grown to reflect increasing modernization, and between 1978 and 2000 there was nearly a 40% increase in per capita total fuel consumption [*Tata Energy Research Institute*, 2000]. This correlates with a booming economy and with increased urban ownership of modern appliances. The urban populations of other South Asian countries have not experienced the same economic growth as India, and biofuels are still common. In Bangladesh, agriculture constitutes the majority of the country's GDP, and the nation relies heavily on agricultural residues [*Miah et al.*, 2003]. Pakistan's urban population has also exhibited high growth, with fossil fuels accounting for 44% of current residential energy consumption [*Food and Agriculture Organization*, 1997a]. In other countries there has been a more modest rate of fuel substitution, and urban fuel mixes have remained relatively unchanged. Auxiliary material Table S4 shows rural and urban per capita biofuel consumption rates for South Asian countries.

2.2.3. Southeast Asia

[18] Southeast Asia's abundant fuelwood and extensive agricultural industries have promoted the continuous use of biofuels in this region. Southeast Asia comprises extremely dense forest areas, and woodfuel shortages have not been noted [*Yevich and Logan*, 2003]. In the absence of external pressures, we assumed that rural per capita biofuel consumption patterns remained relatively stable over the study period. In most countries, fuelwood is preferred over other biofuels. The exceptions to this are Malaysia and Vietnam, where agricultural residues are used to supplement fuelwood, and Thailand, where charcoal consumption has grown to exceed fuelwood by nearly one third [*Food and Agriculture Organization*, 1997a; *Battacharya et al.*, 2000; *Kumar et al.*, 2003]. Urban Southeast Asia shows evidence of extensive fossil-fuel substitution starting in the mid-20th century. As a result, urban per capita biofuel consumption rates dropped during this time: from 0.15 to 0.03 tonnes of oil equivalent (toe)/cap-yr in Indonesia, from 0.12 to 0.05 toe/cap-yr in Malaysia, and from 0.09 to 0.04 toe/cap-yr in the Philippines. Although the urban fuel mix was relatively unchanged for most countries [*Food and Agriculture Organization*, 1997b], Thailand demonstrated a sharp drop in fuelwood consumption in favor of increased reliance upon purchased charcoal, which can be attributed to a growing fuelwood shortage combined with higher urban incomes [*World Bank*, 1985; *Food and Agriculture Organization*, 1997a; *Battacharya et al.*, 2000]. Indonesia is by far the largest energy consumer in Southeast Asia, and its rural population is almost entirely dependent upon biofuels, of which 75% is fuelwood [*World Bank*, 1990]. There has been a slight increase in per capita fuel consumption in recent years due to the incorporation of fossil fuels into the mix, but otherwise the per capita level of fuel consumption has remained stable. Urban Indonesians began substituting fossil fuels in the mid-20th century, and currently biofuels comprise only about one fifth of residential energy consumption. Their

primary use is for cooking, while kerosene and electricity are used for lighting [*World Bank*, 1981].

2.2.4. East Asia

[19] In East Asia, domestic combustion of fuelwood and crop residues grew until the late 1980s, after which growth in urban and rural usage combined was largely halted by the penetration of fossil fuels into the residential sector. China is by far the region's largest consumer of biofuels. In 2002, residential consumption of crop stalks in China was 330 Tg and consumption of fuelwood was 200 Tg [*China Statistics Press*, 2002]. Biofuels represent about 60% of China's residential energy consumption, with the balance mostly served by coal, LPG, natural gas, and electricity. Biogas is increasingly evident in farming communities, though at present it does not supply a large proportion of total energy needs [*Wang et al.*, 2002]. In rural areas of China, biofuel consumption continues to grow in response to population growth despite increasing fossil-fuel substitution. However, regional deforestation and increasing fossil-fuel consumption has created a complex pattern of biofuel consumption. Agricultural residues and fuelwood were used in roughly equal proportions until about 1990 when fuelwood became increasingly scarce in many regions [*Gao and Xu*, 1991; *Lu*, 1993]. In urban China, biofuel consumption has been low since the introduction of fossil fuels at the turn of the century. During 1850–2000, fuelwood was the only biofuel utilized in China's urban areas. Increased affluence in recent years has allowed the urban population to more than double its residential energy consumption, but this growth is entirely attributable to fossil fuels. In North Korea, biofuel use amounts to about 23 Tg annually and in recent years has increasingly made up for shortfalls in coal [*Williams et al.*, 2000].

2.2.5. Latin America

[20] Lacking data on historical urban versus rural biofuel consumption patterns in Latin America, we did not use rural and urban splits in these calculations as we did for most other developing world regions. We did, however, use available rural biofuel data to develop 1850 estimates for each country. Extensive biofuel consumption data are available for recent years, including: IEA energy balances [*International Energy Agency*, 2004b], World Bank country reports, FAO country reports [*Food and Agriculture Organization*, 1993], timber and bagasse data [*Mitchell*, 1998c], and biofuel quantities and usage rates [*Yevich and Logan*, 2003]. On the basis of these sources, we first selected average national per capita estimates of total energy consumption in the modern period. Then we estimated per capita total energy consumption rates for 1850 by analyzing trends in patterns of rural energy consumption. Rates were held constant at 1850 values until the introduction of fossil fuels into the residential sector, which, for most countries, happened in the first half of the 20th century [*Marland et al.*, 2006]. Because much of South America is abundantly forested, there has been little pressure to reduce fuelwood use except in the Altiplano region of Bolivia and parts of Peru, where deforestation has caused a shift to fossil fuels, hydropower, and other biofuels [*World Bank*, 1983c, 1984b]. In these Andean countries with fuelwood scarcity, we estimated that crop residues and dung constituted more than one fourth of total biofuel consumption throughout the period. The majority of Central American countries use more energy per capita than their South American counterparts owing to greater forest density [*Yevich and Logan*, 2003]. Biofuels dominate residential energy consumption in El Salvador, Guatemala, and Honduras [*World Bank*, 1995, 1993, 1987]. Argentina's residential sector relies heavily on charcoal, and we assumed a historical average of one third of total biofuel use. Venezuela, Peru, Paraguay, and Brazil use charcoal for <10% of residential biofuel needs [*Organizacion Latinoamericana de Energia*, 1981; *World Bank*, 1984b, 1984c].

2.2.6. North America

[21] Fuelwood was used extensively in the United States during the 19th century, because it was widely available as forests were cleared for farmland and habitation and there were few energy alternatives. In the mid-19th century, residential per capita fuelwood use for the United Sates was significantly higher than for any other country at 7.4 Mg/person in 1840 [*Reynolds and Pierson*, 1942] and 7.2 Mg/person in 1850 [*Schurr and Netschert*, 1960]. In the late 19th century, the highest U.S. per capita consumption rates were not in cold northern latitudes but in the densely forested southeast [*Reynolds and Pierson*, 1942]. Since no other world regions had significant frontier expansion in vast expanses of virgin forest, no other world region had such high per capita fuelwood consumption rates, despite the high latitudes and cold winters in countries like Russia. These high usage rates of the late 19th century declined dramatically, however, from ~7 Mg/person in 1850 to 1.8 Mg/person by 1900 [*Reynolds and Pierson*, 1942; *Schurr and Netschert*, 1960].

[22] Various published fuelwood trends span segments of our study period. *Reynolds and Pierson* [1942] compiled decadal totals for 1630–1930 based on population, climate, housing conditions, regional wood and coal availability, and fireplace-to-woodstove shifts. *Schurr and Netschert* [1960] calculated total fuelwood consumption at five-year intervals for 1850–1955; they determined that wood accounted for 90.7% of total energy consumption in 1850, 21.0% in 1900, and 2.6% in 1955. The U.S. Forest Products Laboratory (FPL) [*Ince*, 2000] compiled annual roundwood (logs and other round sections of harvested trees) production data for 1900–1998 that included the fuelwood contribution; and the U.S. Energy Information Administration [*Energy Information Administration*, 2004] compiled annual residential, industrial, and commercial fuelwood consumption for 1949 onward.

[23] Although the term "fuelwood" is often associated solely with residential use, we use the term to refer to both residential and industrial consumption, and our term "industrial fuelwood" includes roundwood, black liquor, mill residues, and other tree products. Our general approach to estimating industrial fuelwood use is described in section 2.3, but the special case of the United States was treated differently because of greater data availability. Industrial energy sources available in the United States around 1850 consisted mainly of water and wind power. Railroads were the primary users of industrial fuelwood in the mid-19th century, followed by manufacturing, steam-

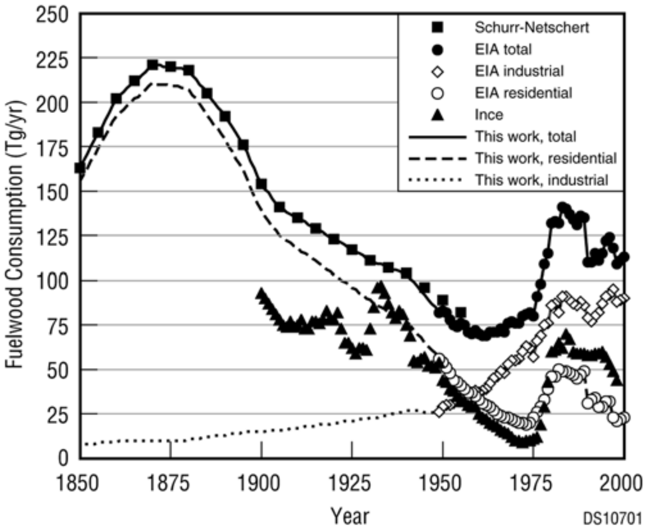

Figure 2. Fuelwood consumption in the United States, 1850–2000.

boats, and charcoal production in the iron industry [*Schurr and Netschert*, 1960]. Since 1900, industrial fuelwood use has been limited mostly to paper and lumber production [*Energy Information Administration*, 1994]. The FPL trend [*Ince*, 2000] differs from Schurr and Netschert data, because the former includes only roundwood used for wood energy and excludes black liquor and mill residues. Schurr and Netschert include mill residues in their data for 1950 but state that they do not include it back in 1850, so their fuelwood consumption trend may be 5–10% low in the early years.

[24] For this study, we combined the EIA and *Schurr and Netschert* [1960] data sets to calculate residential and industrial fuelwood trends for the United States from 1850–2000. We adopted EIA data for the modern period, 1949–2000, adding the small amount of commercially used fuelwood into the industrial trend; we connected the EIA trend to Schurr and Netschert data from 1850–1940 to compile a total fuelwood combustion trend for 1850–2000. We then calculated industrial and residential fuelwood shares for the entire study period from Schurr and Netschert information for the historical period and EIA data for the modern period.

[25] Figure 2 shows the 1850–2000 trends from the major data sources, as well as the composite trends constructed for use in this study. Total fuelwood use peaked at about 220 Tg/yr in 1870 and then declined to about 70 Tg/yr in the 1960s. Residential fuelwood decreased from its peak of about 175 Tg/yr in the 1860s and 1870s, and industrial biofuel use slowly decreased from its peak of about 70 Tg/yr in the 1890s. Industrial biofuel use then began to increase after World War II and has been slowly rising thereafter. After 1974, major increases in petroleum costs resulted in increased fuelwood use in the forest products and residential sectors, as well as public utilities [*Hewett et al.*, 1981]. Disruption of crude oil supply and restricted natural gas availability also contributed to this trend [*Energy Information Administration*, 1994]. As a postscript to the analysis of U.S. fuelwood trends, it is of interest to note that analysis of carbon particles deposited in sediments in Lake Erie has confirmed the shape of the fuelwood usage curve in Figure 2 [*Kralovec et al.*, 2002].

2.2.7. Europe and the Former Soviet Union

[26] In Europe, forest scarcity and coal availability led to tradeoffs between biofuel and coal consumption in the early part of the study period. *Ito and Penner* [2005] assumed that relative changes in biofuel consumption were similar to those in the United States. Here we consider country-specific transitions whose timing was driven by resource availability and technology implementation. Beginning in the mid-1900s, solid fuels were displaced by liquid fuels, natural gas, and centralized production of useful energy, such as heat and electricity. We therefore first estimated total residential energy consumption from records of all fuels, and then the fraction of those needs that were provided by solid fuels, and finally applied a biofuel fraction for solid fuel.

[27] Total residential energy consumption data for the late 20th century came from IEA [*International Energy Agency*, 2004a, 2004b] for fossil fuels, electricity, and centrally produced heat; and biofuel consumption data for 1980 and 1990 came from *van den Broek* [1997]. Mid-20th century records of both fossil fuels and biofuels came from the *Economic Commission for Europe* [1967]. *Shimkin* [1963] gave some data for the former Soviet Union. *Jevons* [1920] and *Hoar* [1930] reported coal use in the United Kingdom in the early 1900s. Estimates for 1950 ranged from 0.15 to 0.8 toe/cap-yr and depended strongly on the country's location. When no data were available for the 1950s, we used per capita figures from an adjoining country of similar latitude and forest cover. Even when country data were extrapolated, estimates were constrained by IEA data for the late 20th century. The greatest uncertainty due to this extrapolation was in Russia, where few data were available and per capita rates for Poland and Ukraine were used. Only about 10% of biofuel use in Eastern Europe was inferred by extrapolation.

[28] For the period between 1850 and 1950, total per capita residential energy consumption could have changed with increasing income. We used the income elasticity of demand to back-project consumption determined in 1950, using country-specific changes in GDP. As real GDP growth outstripped population growth by factors of two to six during this period, even low-income elasticity would affect our back-projected consumption in 1850. Total residential energy use has low-demand elasticity, ranging from 0.1 in Armenia [*Kaiser*, 1999] to 0.4 in the United Kingdom [*Clements and Madlener*, 1999]. Energy during this period was primarily consumed for heating and cooking, which are less elastic than total household energy, so we chose 0.2 as an intermediate value.

[29] Between 1850 and 1950, total energy consumption could also have decreased if forest depletion forced conservation, as it did in the United States before alternatives were widespread. Using state data from the United States, we estimated an "elasticity" of consumption with respect to

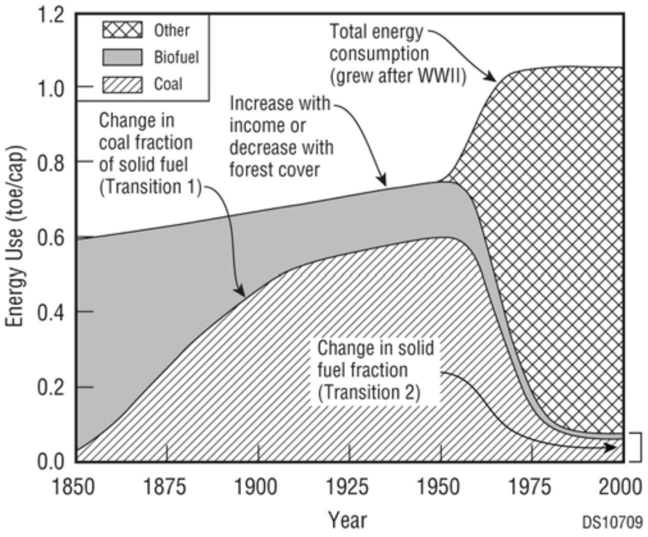

Figure 3. Illustrative residential fuel transitions in European countries (example for Belgium). Transition 3, an increase in wood consumption in the late 20th century, was not significant in this country.

forest cover for periods before coal became dominant. The change in total residential energy use was then represented as

$$\ln\left(\frac{cons_{total}(t)}{cons_{total}(1950)}\right) = \eta_i \ln\left(\frac{GDP(t)}{GDP(1950)}\right) + \eta_f \ln\left(\frac{forest(t)}{forest(1950)}\right), \tag{3}$$

where *cons*(*t*), GDP(t), and forest(t) are consumption, gross domestic product in real dollars, and forest cover, respectively, in year *t*, and η_i and η_f are elasticities with respect to income and forest cover, respectively. We expect that this estimate of biofuel change is rather crude and merely use the procedure to account for large changes. Forest cover was determined, also in a rather crude way, by counting 0.5° × 0.5° pixels in the data of *Klein Goldewijk* [2001]. Predictions using the relationship between forest cover and consumption were also used as checks on early 19th century consumption in countries without recorded data.

[30] For the period between 1850 and 1950, the procedure described above resulted in per capita total energy consumption increases of about 30%. We ignored temporary fluctuations in GDP resulting from depressions or wars. These events undoubtedly decreased residential energy demand and affected emissions. However, emissions during wars are particularly uncertain, because we do not account for high-emitting events such as conflagration. Per capita consumption rates represent a major uncertainty in our estimates of fuel use in the early industrial era. For years after 1950, we used a transformed-normal curve to represent the increase in per capita consumption that was made possible by higher incomes and more convenient fuels. These curves began at the 1950 level and transitioned to an approximately constant level found in the current energy data for each country, guided by observations of individual fuels consumed (particularly *Economic Commission for Europe* [1967]). The transition time was typically 8 to 20 years.

[31] These procedures yielded total residential energy demand, not biofuel demand. We estimated the biofuel fraction by representing three transitions in per capita consumption in each country. In Transition 1, coal gradually replaced biofuel in many countries. We used CDIAC data [*Andres et al.*, 1999; *Marland et al.*, 2006] to estimate 1850 values of residential coal consumption. Although the residential sector is only a fraction of total consumption, we assumed that high per capita residential coal consumption occurred along with high per capita production. We chose the transition time and coal fraction of solid fuel so that our trends matched the earliest recorded values of per capita residential coal consumption. Biofuel consumption rates decreased earlier in Western Europe than in the former Soviet Union, because Transition 1 occurred earlier.

[32] Transition 2 was a conversion away from solid fuels. This usually occurred around the time of the rapid increase in total per capita consumption after World War II. We estimated the parameters of this transition for each country by assembling consumption of different fuels, of electricity, and of central heat. These often came from dissimilar databases, and there is significant uncertainty in determining this transition. Nevertheless, the available data provide a consistent picture throughout Western Europe: in each country, the transition began sometime in the 15 years after World War II, and was frequently accomplished within 8 to 20 years. This transition also occurred, but to a lesser extent, in Eastern Europe and the former Soviet Union. Figure 3 shows representative transitions for one country, Belgium. Finally, Transition 3 occurred in a few countries that preferentially phased out coal in the residential sector because of pollution concerns. In the mid-1950s to mid-1960s, the biofuel fraction of solid fuel grew, as opposed to the trend in the 1800s. We used per capita consumption data and dates of regulations to guide our choices of the coal phase-out transition. Per capita biofuel use as a function of time is then

$$cons_{biofuel}(t) = cons_{total}(t) f_{solid}(t) f_{biofuel}(t), \tag{4}$$

where $cons_{total}(t)$ comes from equation (3), $f_{solid}(t)$ represents Transition 2 (growth of nonsolid fuels), and $f_{biofuel}(t)$ is the fraction of solid fuel that is biofuel (Transitions 1 and 2). Both f_{solid} and $f_{biofuel}$ are transformed-normal curves.

2.2.8. Oceania

[33] Australia, the largest consumer of wood fuels in Oceania, is unusual as a developed country with both high per capita fuelwood consumption and heavy fossil-fuel substitution, probably because the country has extensive wood resources [*Trainer*, 1995]. The main factor limiting Oceania biofuel use has been the substitution of fossil fuels beginning around 1900. We treated this region similarly to Europe, though few data were available. We estimate mid-1900s consumption in Australia and New Zealand as about 0.6 Mg/person, an intermediate value between those

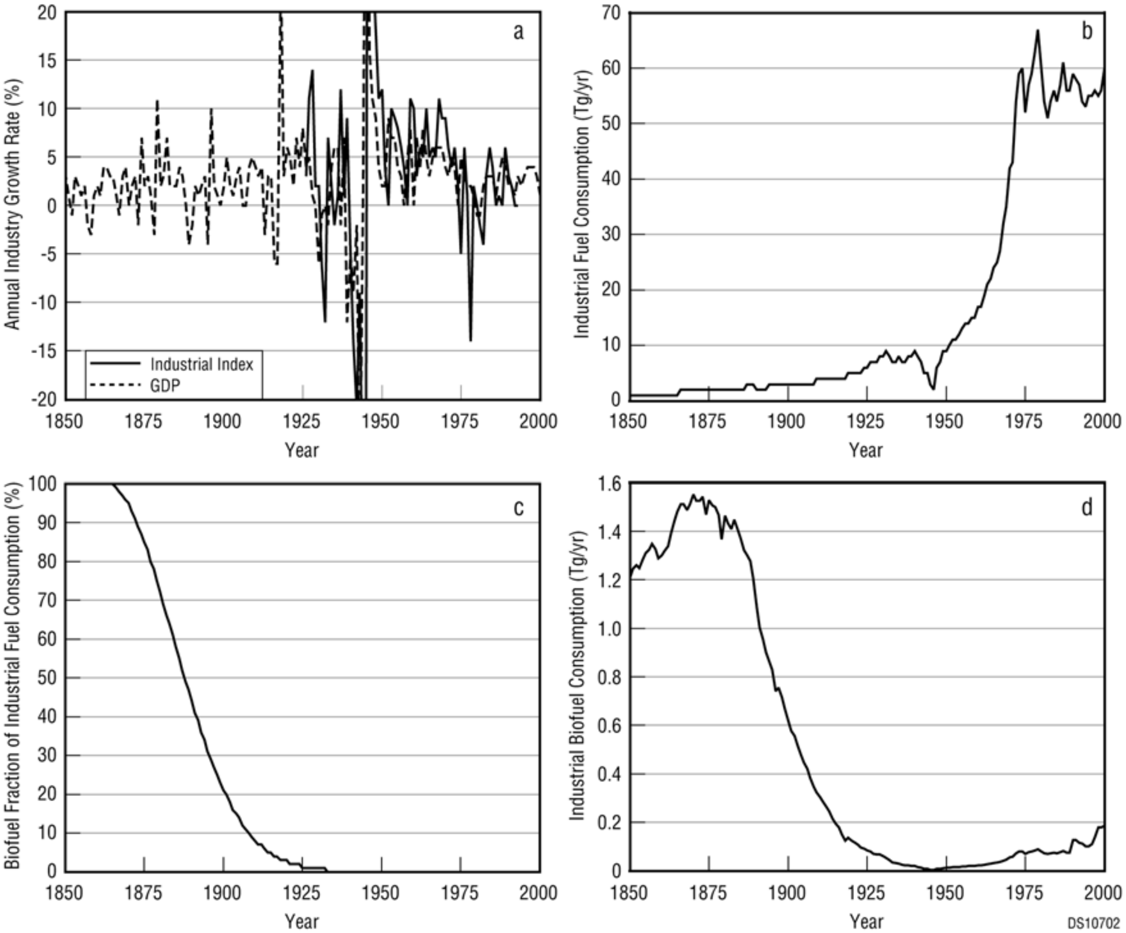

Figure 4. Industrial biofuel calculation methodology (example for the Netherlands). (a) Industry growth rates are calculated from available industrial indices supplemented by GDP growth rates. (b) The growth rates are used to trend total industrial energy use data, available from 1960–2000 for the Netherlands, backward in time. (c) From modern industrial fuel consumption data, biofuel fractions are calculated as discussed in the text. (d) Annual industrial biofuel combustion is calculated by multiplying trends shown in Figures 4b and 4c. Note that there are several values off-scale in Figure 4a. These values are associated with cessation and subsequent reconstruction of industry in the Netherlands during the periods of World Wars I and II. These values are anomalous, and we prefer not to render the meaningful values in the remaining years indecipherable by adjusting the *y* axis range to the highest values.

reported by *International Energy Agency* [2004a] and *Food and Agriculture Organization* [1997a]. Per capita values in Australia dropped from 1960 through the 1980s down to 0.3 Mg/person, followed by a rise to 0.4 Mg/person by 2000 [*Australian Bureau of Agricultural and Resource Economics*, 2005]. Values in New Zealand decreased more steadily to 0.26 Mg/person in 2000.

2.3. Industrial Biofuels

[34] Except for the United States (see approach described in section 2.2.6), we calculated industrial biofuel consumption as a share of total industrial fuel use,

$$IB_{c,t} = IF_{c,t} * fB_{c,t} * EE_{c,t}, \tag{5}$$

where *IB* = industrial sector biofuel consumption; *IF* = total industrial fuel consumption; *fB* = biofuel fraction of *IF*; and *EE* = energy efficiency adjustment.

[35] To determine total industrial fuel combustion, we extrapolated modern industrial fuel use trends [*International Energy Agency*, 2004a, 2004b] back in time using growth factors calculated from annual, country-specific values of the industrial production growth index [*Mitchell*, 1998a, 1998b, 1998c] and from GDP growth values [*Maddison*, 2003]. We used industrial production growth indices whenever available to calculate industry growth rates and interpolated as necessary using constant growth between known values. Data for countries without industrial indices or with significant gaps were derived from GDP growth factors, the industrial index growth factors of similar countries, or the GDP growth factors of similar countries. To illustrate this method, Figure 4a shows the industrial index and GDP growth rates for the Netherlands. Since industrial indices for the Netherlands are only available for 1926–1993 and the industrial index and GDP growth factors are well matched, GDP growth factors were incorporated at both the begin-

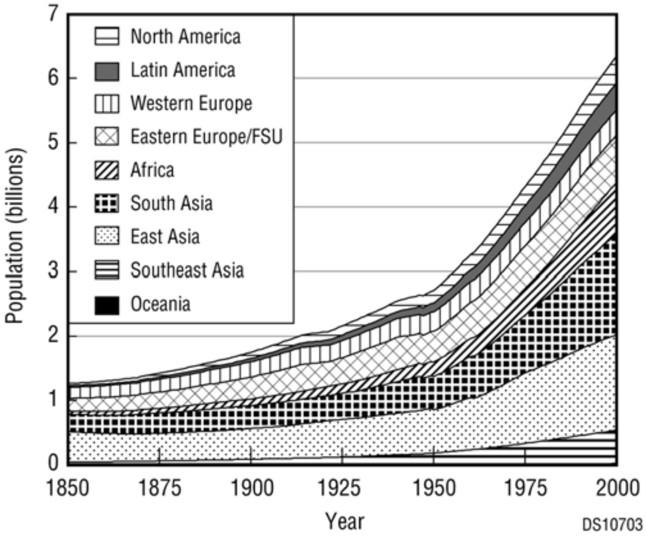

Figure 5. Global population by world region, 1850–2000.

ning and the end of the range to complete the trend from 1850–2000. Netherlands reports industrial energy use since 1960, and we trended the data back (Figure 4b) using our composite growth factors.

[36] After calculating total industrial fuel consumption, we determined biofuel usage as a fraction thereof. Modern fractional biofuel usage is derived from IEA data for 1960–2000. Before fossil fuels were widely used industrially, biofuels, in this case fuelwood, were the main source of industrial fuel, so the fractional use of biofuels was set at 100% from 1850 until the advent of significant fossil-fuel use. The transition period was determined by the period in which CO_2 emissions began to increase dramatically in the CDIAC data [*Marland et al.*, 2006]. Equation (2) was then used to link the historical and present-day trends in fractional biofuel use (Figure 4c). Finally, industrial biofuel consumption was determined as the product of total industrial fuel consumption and biofuel fractions (Figure 4d). We applied an energy efficiency correction factor to reflect the poor combustion efficiencies of historical industrial boilers relative to modern times. This factor was set at 1.4 from 1850–1920, based on a review of conversion efficiencies in old-fashioned stoker-fired industrial boilers [*Popplewell*, 1901], rising at a uniform rate to 1.0 for 1971 and beyond. Because there are more data on the industrial use of bagasse [*International Energy Agency*, 2004a, 2004b], we also compared these bagasse consumption data with our total industrial biofuel values for consistency.

3. Results

3.1. Population

[37] Figure 5 shows our estimates of global population trends from 1850–2000. We estimate that world population grew from 1.27 billion in 1850 to 6.37 billion in 2000. In 1850, the most populated regions were East Asia (475 million, 37%) and South Asia (266 million, 21%), and these regions have remained the most populous over time. Our calculated value for 1850 is in excellent agreement with the value of 1.26 billion in the HYDE database [*Klein Goldewijk*, 2001]. Auxiliary material Figure S1 shows historical trends in rural/urban population splits for four selected developing world regions: Latin America, Africa, South Asia, and East Asia. Urban populations in 1850 were exceedingly small, and they began to be significant first in Latin America in about 1900, subsequently in South Asia and East Asia in about 1925, and shortly thereafter in Africa. In 2000, rural populations were still the largest segment of the total in South Asia, East Asia, and Africa.

3.2 Biofuel Consumption

[38] Figure 6 presents annual average per capita residential biofuel consumption trends for each world region. These curves are obtained by aggregating the country-level trends of the kind presented in Figure 1. In all world regions, per capita biofuel consumption has declined during the period of this study. In some developing world regions, such as South Asia, East Asia, and Africa, the rate of decline has been small, while in the developed world regions the decline has been more rapid, none more so than in North America where the historical high consumption rate of ~7 Mg/person in 1850 has fallen to ~0.1 Mg/person in 2000. Throughout most of the rest of the world, per capita consumption rates were in the range of 0.4–0.8 Mg/person during 1850–1950, declining to 0.1–0.6 Mg/person since 1950.

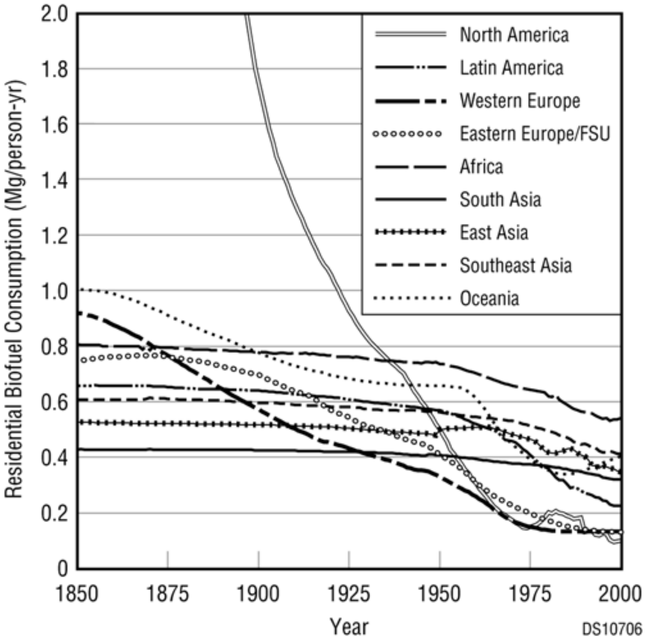

Figure 6. Annual per capita residential biofuel consumption trends, 1985–2000, by world region. The curve for North America reaches its maximum value of 5.2 Mg/person in 1850, but we have expanded the *y* axis range, so that trends in other world regions may be examined.

[39] In the final year of our trend, 2000, we estimate that total global biofuel consumption was 2457 Tg (Table 1), 80% (1959 Tg) in the residential sector and 20% (498 Tg) in the industrial sector. In the residential sector, the split by fuel types is: 1351 Tg fuelwood (69% of residential biofuel consumption), 495 Tg crop residues (25%), 75 Tg dung (4%), and 39 Tg charcoal (2%). Industrial biofuel consumption was highest in North America (119 Tg, or 24% of the global total), Latin America (104 Tg, 21%) and South Asia (91 Tg, 18%). Residential biofuel consumption was highest in East Asia (516 Tg, or 26% of the global total), South Asia (497 Tg, 25%), and Africa (438 Tg, 22%). Table 1 also shows our global, fuel-specific trends for 1980, 1985, 1990, and 1995, and compares them with other estimates.

[40] Figure 7 presents the time series of global trends from 1850 to 2000 by world region (upper) and by fuel type (lower). Regional biofuel consumption estimates for every decade can be found in auxiliary material Table S5. Figure 8 shows the trends by fuel type in each world region. Globally, biofuel consumption rose from 1006 Tg in 1850 to the year-2000 value of 2457 Tg, an increase of 144%. World population grew by 402% from 1.27 to 6.37 billion in the same period. Biofuel consumption grew by more than a factor of ten in Africa and Latin America between 1850 and 2000. In Asia, the growth was not quite so dramatic because significant quantities were already being consumed in 1850. In contrast, consumption in North America declined from 183 Tg in 1850 to 159 Tg in 2000, as fossil fuels supplanted the intensive fuelwood economy of the 1800s. During the mid-1800s, global biofuel consumption grew, as wood fueled the surging industrial economy of the United States and usage grew also in Europe and South Asia. After 1870, however, the rate of increase in global biofuel consumption slowed down markedly, owing to the burgeoning use of fossil fuels, world wars, slumping economies, and relatively low population growth in the developing world. Between 1870 and 1950, annual global biofuel use grew by only 305 Tg or 27% in 80 years, from 1141 Tg in 1870 to 1446 Tg in 1950. In the post-WWII period, biofuel consumption increased dramatically, as rural populations in the developing world grew rapidly and industrial fuelwood regained some popularity. In the 50-year period from 1950 to 2000, annual global biofuel consumption grew by 70% from 1446 Tg to 2457 Tg.

[41] Figure 9 presents biofuel consumption in 1850, 1900, 1950, and 2000 gridded according to the global population distributions in each year. The methodology follows that described by *Bond et al.* [2004], except that biofuel consumption is distributed between rural and urban populations in this work, whereas previous work used only rural populations. The urban and rural population distributions of *Klein Goldewijk* [2005], which account for migration over time, were used.

3.3. Uncertainty Analysis

[42] The greatest sources of uncertainty in our historical biofuel calculations are the residential per capita biofuel consumption rates; other significant sources of uncertainty are industry growth rates, population sizes, and assumed biofuel fractions of total fuel use. We calculated uncertainties for these four sources of uncertainty using a propagation-of-error technique described in detail by *Streets et al.* [2003]. Coefficients of variation (CV) are calculated at 25-year intervals over the study period. We combine CV values using Goodman's formula for the product of variables:

Table 1. Global and Regional Biofuel Consumption Estimates for Recent Years[a]

	Residential						
World Region	Fuelwood	Crop Residues	Dung	Charcoal	Industrial	Total	Year
North America	41	0	0	0	119	159	2000
Latin America	80	0	0	16	104	199	2000
Africa	372	52	0	14	61	499	2000
Western Europe	51	0	0	0	47	98	2000
Eastern Europe/FSU	96	0	0	0	6	102	2000
South Asia	344	76	75	3	91	589	2000
East Asia	193	323	0	0	9	525	2000
Southeast Asia	164	43	0	6	46	260	2000
Oceania	10	0	0	0	16	26	2000
Global Total	1351	495	75	39	498	2457	2000
			Other Global Estimates				
This work	1298	471	75	40	461	2346	1995[b]
	1316	414	77	38	394	2239	1990[b]
	1280	400	77	33	366	2157	1985[b]
	1213	364	77	27	328	2010	1980[b]
Hall et al. [1994]	1242[c]	-	-	c[c]	-	4106	1987
Ludwig et al. [2003]	1062[d]	-	-	24[d]	-	3199	1995
Yevich and Logan [2003]	1714[c]	597	136	c[c]	-	2447	1985
Junker and Liousse [2006]	-	-	-	-	-	∼2280[e]	2000

[a] Units are Tg/yr. Rows and columns may not sum owing to rounding.

[b] See auxiliary material Table S5 for regional breakdowns in these years.

[c] Fuelwood estimate includes charcoal.

[d] Fuelwood and charcoal values are for 1993.

[e] Value are estimated from Figure 2 of their paper; no numerical value is given.

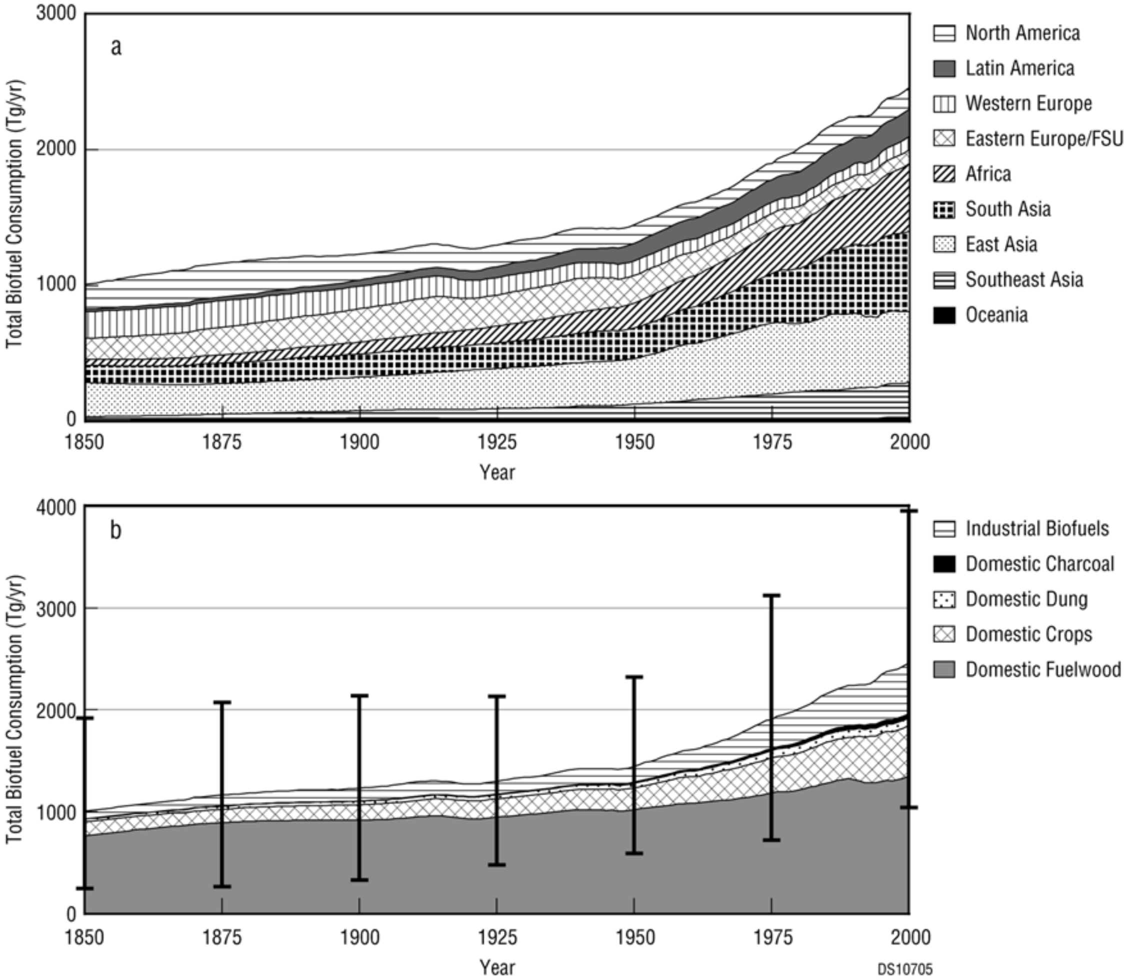

Figure 7. Global biofuel consumption trends, 1985–2000, by (a) world region and (b) fuel type, showing 95% confidence intervals.

uncertainties in dependent variables are added linearly across sectors and within regions, and uncertainties in independent variables are combined in quadrature. Individual CV values were estimated using expert judgment based on known modern uncertainties. The CV values for population were estimated on the basis of previous attempts to characterize the uncertainty of population estimates and the perceived reliability of modern census data [*Mitchell*, 1998a, 1998b, 1998c; *Durand*, 1977]; uncertainties decrease from 1850 to 2000 as better census records become available, with higher certainty in developed than developing nations. Residential per capital biofuel consumption CV values were derived from an examination of the range of modern estimates (FAO website, 1999) [also *Food and Agriculture Organization*, 1997a; *International Energy Agency*, 2004a, 2004b]; values were held relatively constant and high for developing nations where biofuel use is poorly documented, while values for developed countries increased back in time. Two types of industrial biofuel CV values were estimated. The CV for industrial energy use were lowest in developed countries with better records and decreased from 1850–2000. CV values for the fraction of total industrial energy use from biofuels were low in historic times, when the majority of industrial energy was assumed to come from biofuels (except in Europe), as well as in modern times, when energy consumption patterns are known. The highest fractional CV values are for the early 1900s when fuel mixes are not well known.

[43] The 95% confidence intervals for total global biofuel consumption are shown in Figure 7b. Uncertainty decreased from ±82% in 1850 to ±55% in 1950, increasing slightly to ±58% in 1975 and returning to ±55% in 2000. Uncertainty in the residential biofuel consumption estimates is greatest in the early years, owing to a lack of knowledge about historical combustion practices and per capita rates of biofuel use; however, for the early years we can at least be confident that biofuel use was close to 100% of the fuel mix. Over time, the uncertainty in residential biofuel use slowly decreases, but even the modern data are acknowledged by their compilers to be quite uncertain in many parts of the developing world. As discussed in the previous

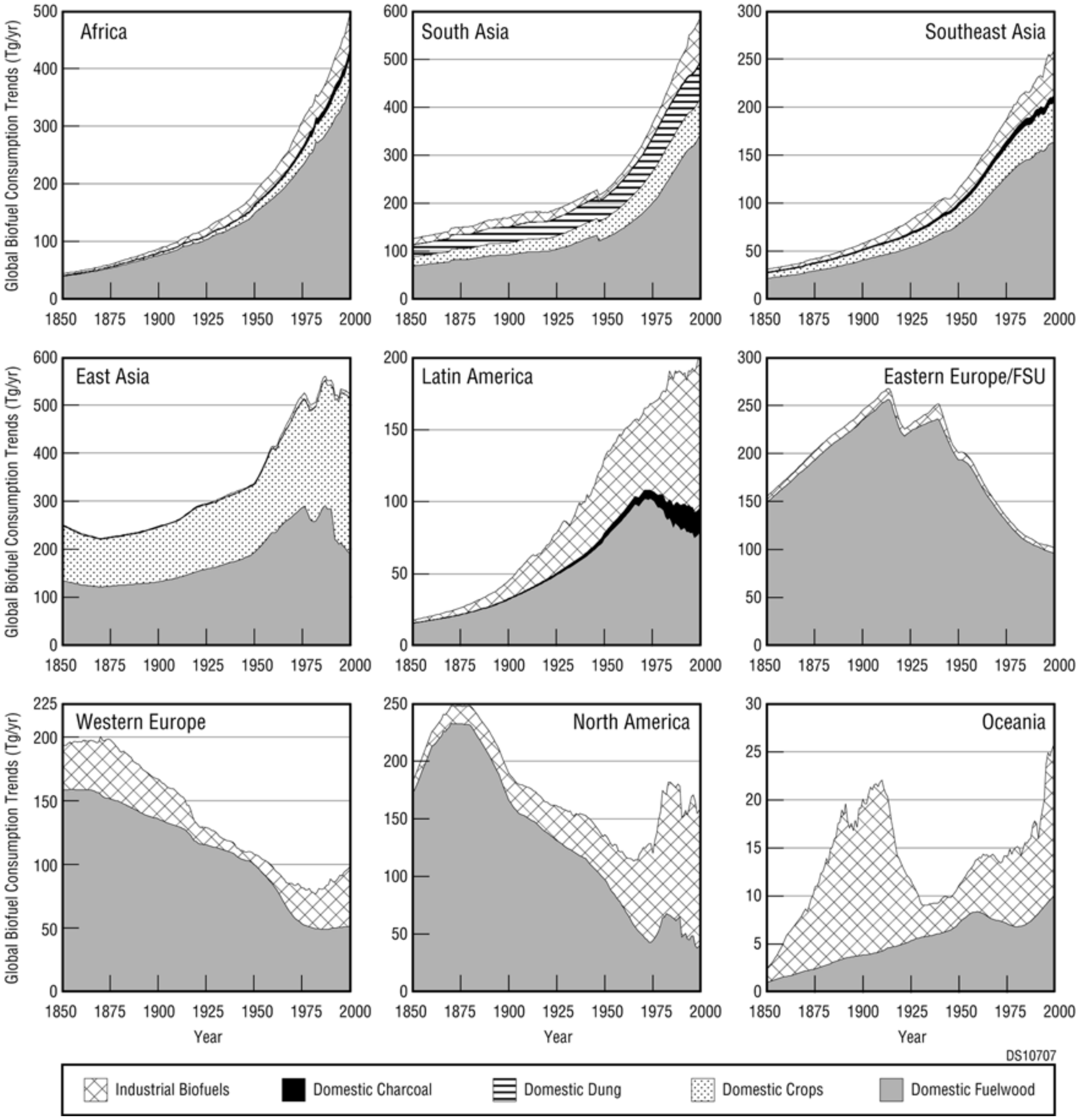

Figure 8. Global biofuel consumption trends in each world region, 1850–2000 (Tg/yr).

paragraph, uncertainty in our estimates of industrial biofuel consumption is largest in the middle of the study period.

4. Discussion and Conclusions

[44] The most detailed investigation of global biofuel use is the assessment by *Yevich and Logan* [2003]; they estimated that 2447 Tg of biofuels were consumed in 1985 (see Table 1). Our estimate for 1985 is 2157 Tg, with 1791 Tg directly consumed in the residential sector and an additional 366 Tg consumed industrially. There is good agreement between the two sets of estimates for most regions for that year. In some regions our estimates are lower than those of *Yevich and Logan* [2003], which can be partly explained by methodological differences and partly by different classifications of residential and industrial uses. The higher estimate by *Hall et al.* [1994] for 1987 of 4106 Tg is driven by older biofuel use data and default values for annual biofuel consumption rates of 1 Mg/person in rural areas and 0.5 Mg/person in urban areas (see discussion by *Yevich and Logan* [2003]), which can be seen from Figure 1 to be higher than our research suggests. *Ito and Penner* [2005] developed a historical inventory of carbonaceous aerosols for the period 1870–2000, which included estimates of biofuel use. They estimated that fuelwood consumption in developed countries declined from 478 Tg in 1870 to 226 Tg in 2000. Our estimates for this time period and for the same countries are 650 Tg in 1870 and 385 Tg in 2000 for total biofuel consumption, and 575 Tg in 1870 and 198 Tg in 2000 for residential fuelwood consumption. Though the approach taken by *Ito and Penner* [2005] is different than our study, the results are similar.

[45] We conclude that global biofuel consumption has been historically high in the past. Prior to the late 1800s,

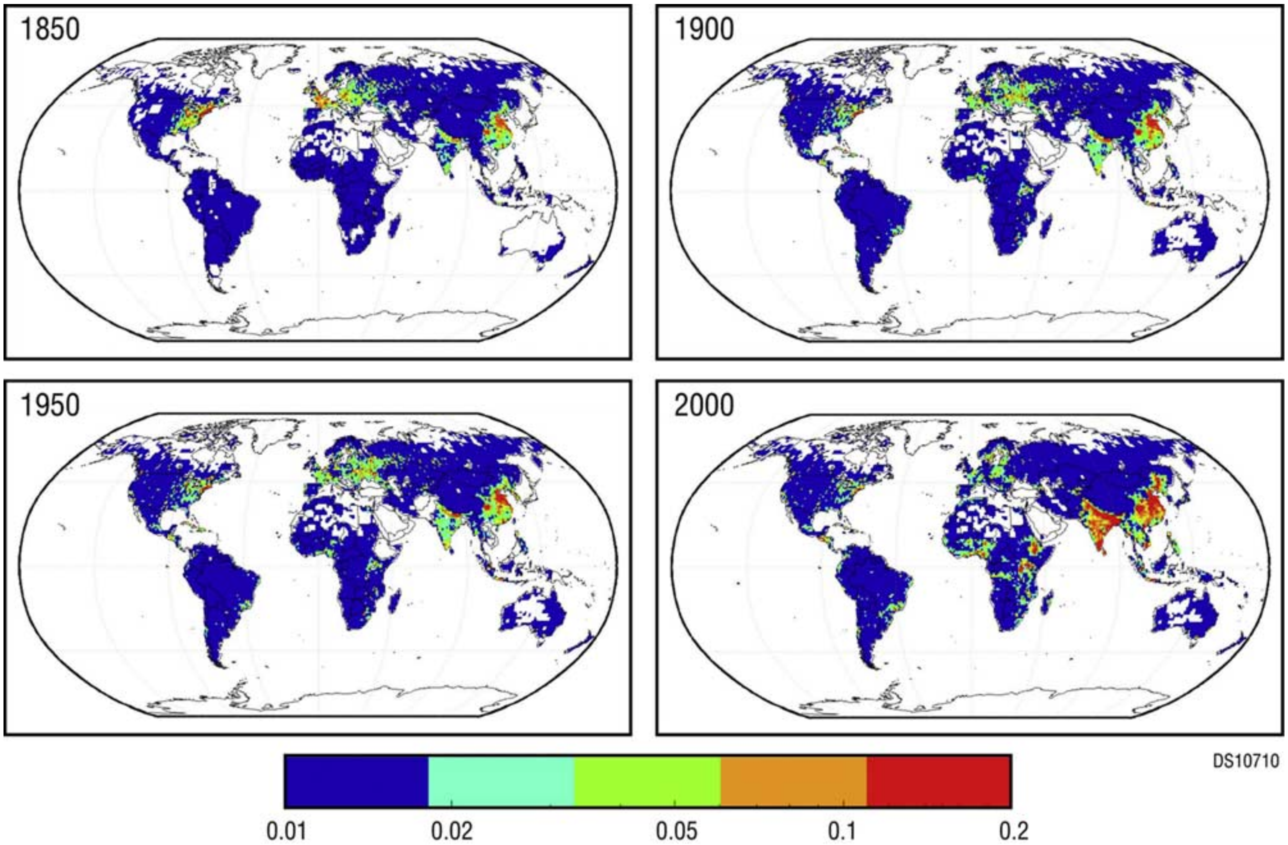

Figure 9. Spatial distribution of global biofuel consumption (kg/m^2-yr) in 1850, 1900, 1950, and 2000.

fuelwood represented the major source of energy everywhere except for emerging coal usage in Western Europe. The beginnings of the industrial revolution and land clearing in North America drove the high levels of fuelwood use. As fossil fuels spread in the late 1800s and early 1900s, they quickly subsumed a large fraction of the rapidly increasing energy use and dampened the growth in biofuel use. After WWII, however, rural populations increased dramatically in the developing world and triggered renewed growth in biofuel consumption. Though patterns of biofuel use have changed in the last two decades, renewed interest in industrial biofuels and a stabilization of fuelwood use have reinforced the rate of increase of global biofuel consumption. The shape of the biofuel trend in Figure 7 is in distinct contrast to the trend in fossil-fuel use [see *Andres et al.*, 1999; *Marland et al.*, 2006; *Bond et al.*, 2007], which shows very low usage rates in the mid-19th century, rising rapidly and continuously thereafter.

[46] Knowing the relative emission rates of primary carbonaceous aerosols from the different fuels and sectors, we would expect biofuel combustion to dominate emissions of organic carbon in the historical period and to be a major contributor to black carbon emissions (see companion paper [*Bond et al.*, 2007]), both of which will have a major influence on atmospheric aerosol concentrations. Thus this detailed bottom-up inventory of biofuel combustion and its companion paper will enable climate modelers to better understand the extent of human influence on climate since the industrial revolution. To omit or incorrectly quantify the amount of biofuel used around the world in historical climate-change modeling is to mischaracterize anthropogenic interference in climate. The community needs to develop similar historical trends in open biomass burning (forest fires, etc.), though these will be very difficult to compile and will be more uncertain than the biofuel inventory. Work on this topic has been reported by *Crutzen and Zimmerman* [1991], *van Aardenne et al.* [2001], *Ito and Penner* [2005], *Mouillot and Field* [2005], and *Mouillot et al.* [2006]; their studies suggest that emissions from open biomass burning have increased during the course of the 20th century, but all authors caution that more work is needed to confirm the findings.

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